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Search for charged Higgs bosons through the violation of lepton universality in $t\bar{t}$ events using pp collision data at $\sqrt{s} = 7$ TeV with the ATLAS experiment

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Abstract: In several extensions of the Standard Model, the top quark can decay into a bottom quark and a light charged Higgs boson H^+, $t \to bH^+$, in addition to the Standard Model decay $t \to bW$. Since W bosons decay to the three lepton generations equally, while H^+ may predominantly decay into $\tau\nu$, charged Higgs bosons can be searched for using the violation of lepton universality in top quark decays. The analysis in this paper is based on $4.6\,\mathrm{fb}^{-1}$ of proton-proton collision data at $\sqrt{s} = 7$ TeV collected by the ATLAS experiment at the Large Hadron Collider. Signatures containing leptons (e or μ) and/or a hadronically decaying τ (τ_{had}) are used. Event yield ratios between $e+\tau_{\mathrm{had}}$ and $e+\mu$, as well as between $\mu+\tau_{\mathrm{had}}$ and $\mu+e$, final states are measured in the data and compared to predictions from simulations. This ratio-based method reduces the impact of systematic uncertainties in the analysis. No significant deviation from the Standard Model predictions is observed. With the assumption that the branching fraction $\mathcal{B}(H^+ \to \tau\nu)$ is 100%, upper limits in the range 3.2%–4.4% can be placed on the branching fraction $\mathcal{B}(t \to bH^+)$ for charged Higgs boson masses m_{H^+} in the range 90–140 GeV. After combination with results from a search for charged Higgs bosons in $t\bar{t}$ decays using the τ_{had}+jets final state, upper limits on $\mathcal{B}(t \to bH^+)$ can be set in the range 0.8%–3.4%, for m_{H^+} in the range 90–160 GeV.

Keywords: Hadron-Hadron Scattering

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Contents

1 Introduction

Several non-minimal Higgs scenarios, e.g. Two Higgs Doublet Models (2HDM) [1] predict the existence of charged Higgs bosons (H^+ and H^-).[1] Their observation would clearly indicate physics beyond the Standard Model (SM), because this theory contains no elementary charged scalar particle. In several models, e.g. a type-II 2HDM describing the Higgs sector of the Minimal Supersymmetric extension of the Standard Model (MSSM) [2–6], the main production mode for charged Higgs bosons with a mass m_{H^+} smaller than the top quark mass (m_{top}) is through top quark decays $t \to bH^+$. The dominant source of top quarks at the Large Hadron Collider (LHC) is through $t\bar{t}$ production.[2]

The combined LEP lower limit on the charged Higgs boson mass is about 90 GeV [7]. Results from direct searches for charged Higgs bosons decaying via $H^+ \to \tau\nu$ using 4.6 fb^{-1} of LHC data were recently presented by the ATLAS collaboration [8], with upper limits on the branching fraction $\mathcal{B}(t \to bH^+)$ between 5% and 1% for charged Higgs boson masses ranging from 90 GeV to 160 GeV, respectively. Using about 2 fb^{-1} of LHC data, the CMS collaboration established upper limits on $\mathcal{B}(t \to bH^+)$ in the range 4–2% for charged Higgs boson masses between 80 GeV to 160 GeV [9]. In all of these measurements, as well as in this paper (unless otherwise specified), the assumption $\mathcal{B}(H^+ \to \tau\nu) = 100\%$ is made.

[1]In the following, charged Higgs bosons are denoted H^+, with the charge-conjugate H^- always implied. Hence, τ denotes a positively charged τ lepton.

[2]Since the cross section for H^+ production from events containing a single top quark is much smaller, this production mode is not considered here.

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This paper uses an alternative technique [10] for H^+ searches in the mass range 90–160 GeV. Instead of using the shape of discriminating variables in order to search for a local excess of events above the predicted SM background, this analysis is based on the measurement of a ratio of event yields between two $t\bar{t}$ final states, which in turn allows for the cancellation of most of the systematic uncertainties. In top quark decays, W bosons decay equally to leptons of the three generations, while H^+ may decay predominantly into $\tau\nu$. Hence, an excess of $t\bar{t}$ events with at least one hadronically decaying τ lepton ($\tau_{\rm had}$) in the final state, as compared to the rate for $t\bar{t}$ events with only electrons and/or muons, is a signature for charged Higgs bosons. A measurement of event yield ratios R_l for $t\bar{t} \to b\bar{b} + l\tau_{\rm had} + N\nu$ and $t\bar{t} \to b\bar{b} + ll' + N\nu$, where $N\nu$ stands for any number of neutrinos and where l and l' are electrons and muons, with $l \neq l'$, is performed:

$$R_l = \frac{\mathcal{B}(t\bar{t} \to b\bar{b} + l\tau_{\rm had} + N\nu)}{\mathcal{B}(t\bar{t} \to b\bar{b} + ll' + N\nu)}. \tag{1.1}$$

This study is performed in a model-independent way, and so exclusion limits are given in terms of $\mathcal{B}(t \to bH^+)$, as well as in the $m_h^{\rm max}$ scenario [11] of the MSSM. The results are based on 4.6 fb^{-1} of data from pp collisions at $\sqrt{s} = 7$ TeV, collected in 2011 with the ATLAS experiment [12] at the LHC. These data, as well as the simulated samples used in the analysis, are the same as in ref. [8] and are described briefly in section 2. Then, in section 3, an event selection aimed at collecting a data sample enriched in $t\bar{t}$ events is presented, together with the data-driven methods to estimate the backgrounds due to misidentified electrons, muons and hadronically decaying τ leptons. Exclusion limits in terms of $\mathcal{B}(t \to bH^+)$ and $\tan\beta$ are discussed in section 4, based on the measured ratios among event yields in $\tau_{\rm had}$+lepton and dilepton final states. Finally, a summary is given in section 5.

2 ATLAS data and simulated events

The ATLAS detector [12] consists of an inner tracking detector with coverage in pseudorapidity[3] up to $|\eta| = 2.5$, surrounded by a thin 2 T superconducting solenoid, a calorimeter system extending up to $|\eta| = 4.9$ for the detection of electrons, photons and hadronic jets, and a large muon spectrometer extending up to $|\eta| = 2.7$ that 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.

In ATLAS, electrons are reconstructed by matching clustered energy deposits in the electromagnetic calorimeter to tracks reconstructed in the inner detector, and muons are required to contain matching inner detector and muon spectrometer tracks. The combination of all sub-systems provides precise lepton measurements in the pseudorapidity range

[3]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

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$|\eta| < 2.5$. Jets, as well as the magnitude of the missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$, are reconstructed using energy deposits over the full coverage of the calorimeters, up to $|\eta| = 4.9$. The anti-k_t algorithm [13, 14] with a radius parameter value of $R = 0.4$ is used for jet reconstruction. At least 75% of the tracks associated to a jet (weighted by their transverse momenta) must point to the primary vertex, corresponding to the hardest interaction. This requirement on the "Jet Vertex Fraction" [15] allows the identification of jets originating from the hard-scatter interaction. An algorithm combining impact-parameter information with the explicit observation of a secondary vertex [16] is used in order to identify jets initiated by b-quarks, within $|\eta| < 2.4$. The working point chosen for this study corresponds to an average efficiency of about 70% for b-jets with $p_{\mathrm{T}} > 20$ GeV in $t\bar{t}$ events and a rejection factor of about 130 for light-quark jets. In order to reconstruct hadronically decaying τ leptons, anti-k_t jets with either one or three associated tracks, depositing $E_{\mathrm{T}} > 10$ GeV in the calorimeter, are considered as τ candidates [17]. Dedicated algorithms are used to reject electrons and muons. The τ candidates are further required to have a visible transverse momentum $p_{\mathrm{T}}^{\tau} > 20$ GeV and to be within $|\eta| < 2.3$. The hadronic τ decays are identified using a likelihood criterion designed to discriminate against quark- and gluon-initiated jets. The working point chosen for this study corresponds to an efficiency of about 30% for hadronically decaying τ leptons with $p_{\mathrm{T}}^{\tau} > 20$ GeV in $Z \to \tau\tau$ events, leading to a rejection factor of about 100–1000 for jets. Selected τ candidates fulfilling the identification criteria are referred to as "τ jets". When objects selected using the criteria above overlap geometrically, the following procedures are applied, in this order: muons are rejected if found within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.4$ of any jet with $p_{\mathrm{T}} > 25$ GeV; a τ candidate is rejected if found within $\Delta R < 0.4$ of a b-tagged jet, or within $\Delta R < 0.2$ of a selected muon or electron; jets are removed if they are within $\Delta R < 0.2$ of a selected τ jet or electron.

The same full 2011 data set and simulated samples as the analysis in ref. [8] are used, corresponding to an integrated luminosity of 4.6 fb^{-1}, with an uncertainty of 3.9% [18, 19]. In addition to the SM pair production and decay of top quarks, $t\bar{t} \to b\bar{b}W^+W^-$,[4] the background processes include the production of single top quark, W+jets, Z/γ^*+jets, diboson, and multi-jet events. Except for the last, which is estimated using data-driven methods, the SM backgrounds are determined using the simulated samples summarised in table 1. In addition to the SM background samples, three types of signal samples are produced with PYTHIA 6.425 [20] for 90 GeV $< m_{H^+} <$ 160 GeV: $t\bar{t} \to b\bar{b}H^+W^-$, $t\bar{t} \to b\bar{b}H^-W^+$ and $t\bar{t} \to b\bar{b}H^+H^-$, where charged Higgs bosons decay as $H^+ \to \tau\nu$. TAUOLA 1.20 [21] is used for τ decays, and PHOTOS 2.15 [22] is used for photon radiation from charged leptons. All generated events are propagated through a detailed GEANT4 simulation [23, 24], and they are reconstructed using the same algorithms as the data.

3 Event selection and background determination

This analysis uses events passing a single-lepton trigger with an E_{T} threshold of 20 GeV or 22 GeV for electrons and a p_{T} threshold of 18 GeV for muons. In order to select a sample

[4] In the simulated SM $t\bar{t}$ events, all leptonic W decay modes have the same branching fraction (10.8%).

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Process	Generator		Cross section [pb]	
SM $t\bar{t}$ with at least one lepton $\ell = e,\ \mu,\ \tau$	MC@NLO 4.01	[25]	91	[26]
Single top quark t-channel (with ℓ)	AcerMC 3.8	[27]	21	[28]
Single top quark s-channel (with ℓ)	MC@NLO 4.01	[25]	1.5	[29]
Single top quark Wt-channel (inclusive)	MC@NLO 4.01	[25]	16	[30]
$W \to \ell\nu$	ALPGEN 2.13	[31]	3.1×10^4	[32]
$Z/\gamma^* \to \ell\ell$ with $m(\ell\ell) > 10$ GeV	ALPGEN 2.13	[31]	1.5×10^4	[33]
WW	HERWIG 6.520	[34]	17	[35]
ZZ	HERWIG 6.520	[34]	1.3	[35]
WZ	HERWIG 6.520	[34]	5.5	[35]
H^+ signal with $\mathcal{B}(t \to bH^+) = 3\%$	PYTHIA 6.425	[20]	9.9	

Table 1. Cross sections for the simulated processes and the generators used to model them. All background cross sections are normalised to next-to-next-to-leading-order (NNLO) predictions, except for diboson event production where the next-to-leading-order prediction (NLO) is used. For the diboson events, a filter is applied at the generator level, by requiring at least one electron or muon with $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.8$.

enriched in $t\bar{t}$ events, the following requirements are made:

- one charged lepton l (e, μ) having $E_{\mathrm{T}} > 25$ GeV (e) or $p_{\mathrm{T}} > 25$ GeV (μ) and matched to the corresponding trigger object;
- at least two jets having $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.4$, including exactly two b-tags;
- either exactly one τ jet with $p_{\mathrm{T}}^{\tau} > 25$ GeV and $|\eta| < 2.3$ with no additional charged lepton, or exactly one additional charged lepton l' with E_{T} or p_{T} above 25 GeV and a different flavour than the trigger-matched lepton;
- $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV.

At this stage, the selected events are classified into two categories according to the single-lepton trigger that they fire: an electron trigger (EL) or a muon trigger (MU). Each category contains τ_{had}+lepton and dilepton (ll') events. The lepton appearing first in the final state is, by convention, matched to the corresponding trigger object. The EL category therefore consists of $e + \tau_{\mathrm{had}}$ and $e + \mu$ events, while the MU category contains $\mu + \tau_{\mathrm{had}}$ and $\mu + e$ events. Events firing both a single-electron trigger and a single-muon trigger are assigned to both categories, and accounted for in the combined limit setting, see section 4.3.

The analysis uses the generalised transverse mass m_{T2}^{H} [36] as a selection variable. By construction, it gives an event-by-event lower bound on the mass of the charged (W or Higgs) boson produced in the top quark decay. Hence, it is larger than the true charged Higgs boson mass m_{H^+} and smaller than m_{top}. For incorrect pairings of τ jets or leptons with b-jets, the numerical determination of m_{T2}^{H} may fail, hence only events with $m_{\mathrm{T2}}^{H} > 0$ are kept in the following.

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3.1 Backgrounds due to misidentified electrons and muons

A significant background for the search described in this paper consists of events with reconstructed electrons and muons arising from the semileptonic decay of hadrons with b- or c-quarks, from the decay-in-flight of π or K mesons and, in the case of electrons, from π^0 mesons, photon conversions or shower fluctuations. These are referred to as "misidentified leptons" in the following. Two data samples are defined, which differ only in the lepton identification criteria. The *tight* sample corresponds to the selection used in the analysis and contains mostly events with real leptons. The *loose* sample is obtained by loosening the isolation and identification requirements, and it contains mostly events with misidentified leptons.[5] 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, with the same method as in ref. [8]. In the final parameterisation of p_{r} and p_{m}, dependencies on the pseudorapidity of the lepton, its distance ΔR to the nearest jet and the leading jet p_{T} are taken into account. Based on these efficiencies, the number of misidentified leptons passing the final requirements can be calculated by weighting each event in the data sample with one loose lepton, according to the following per-lepton weights w_l:

- for a loose but not tight lepton, $w_{l\mathrm{L}} = \dfrac{p_{\mathrm{m}} p_{\mathrm{r}}}{(p_{\mathrm{r}} - p_{\mathrm{m}})}$;
- for a tight lepton, $w_{l\mathrm{T}} = \dfrac{p_{\mathrm{m}}(p_{\mathrm{r}} - 1)}{(p_{\mathrm{r}} - p_{\mathrm{m}})}$.

3.2 Backgrounds due to misidentified τ jets

About 51% of the simulated $t\bar{t}$ events in the τ_{had}+lepton final state contain a τ jet matched to a hadronically decaying τ lepton at the generator level. In the other events, the τ jet is called "misidentified". It originates from leptons (e, μ) in 3% of the simulated events and hadronic objects (initiated by light quarks, b-quarks or gluons) in 46%. Data-driven methods are used in order to determine the probability of misidentification from electrons and hadronic jets. In the case of electrons, the misidentification probabilities are measured using a $Z \to ee$ control region in the data [17] and then applied to the simulated events, as in the analysis in ref. [8]. The majority of misidentified τ jets in the final event selection originate from jets, for which the misidentification probability depends on the initial parton (light quark, heavy-flavour quark or gluon). All jet types occur in $t\bar{t}$ events, and it is not possible to accurately predict the fraction of each of them, potentially leading to a large systematic uncertainty on the jet$\to \tau_{\mathrm{had}}$ misidentification probability. However, the influence of all jet types other than light-quark jets can effectively be eliminated by categorising all events in terms of the charge of the lepton relative to the τ jet as opposite-sign (OS) or same-sign (SS) events. All processes with gluon and b-quark jets produce positively and negatively charged misidentified τ objects at the same rate. On the other hand, the light-quark jet component in SS events represents both charge misreconstruction and quarks which fragment such that the leading charged particle does not have the same charge as the initial quark. Giving a negative weight to the SS events therefore cancels, on

[5]By construction, the tight sample is a subset of the loose sample.

average, the gluon and heavy-flavour-quark jet contributions from the OS events, leaving only light-quark jets misidentified as τ jets.

The rate at which light-quark jets are misidentified as τ candidates is derived using a region enriched with $W + {>}2$ jets events[6] in the data, selected by requiring:

- exactly one electron or muon with E_{T} or p_{T} larger than 25 GeV;
- at least one τ candidate;
- at least two jets in addition to the τ candidate(s), none of them being b-tagged;
- $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV.

In order to reduce the contribution from events with a true τ lepton, mostly from Z+jets events, a requirement on the transverse mass m_{T} is made:

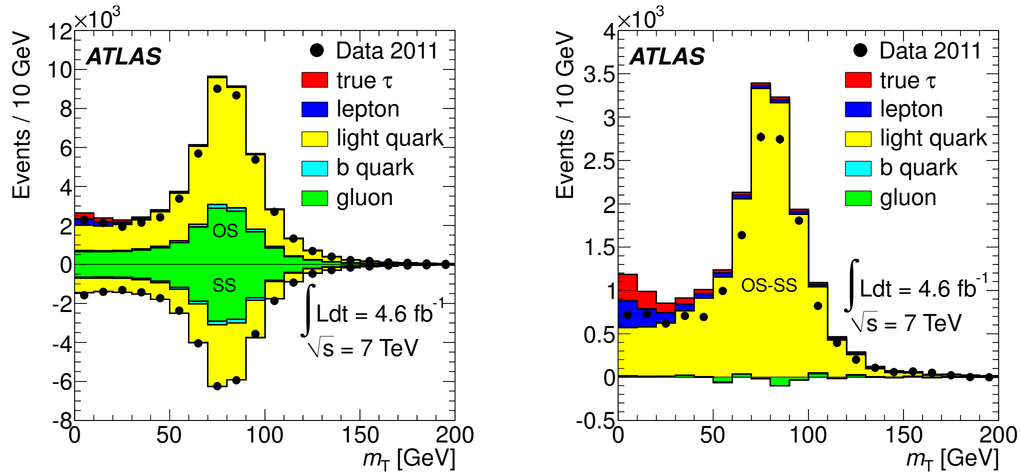
$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{l} E_{\mathrm{T}}^{\mathrm{miss}}(1 - \cos \Delta\phi_{l,\mathrm{miss}})} > 30 \text{ GeV}, \tag{3.1}$$

where $\Delta\phi_{l,\mathrm{miss}}$ is the azimuthal angle between the lepton and the direction of the missing momentum. The $W + {>}2$ jets events are classified as OS and SS events using the charges of the lepton and the τ candidate. Figure 1 shows the m_{T} distribution for OS, SS and OS-SS events fulfilling the $W + {>}2$ jets selection. This demonstrates the cancellation of heavy-flavour-quark and gluon contributions.

The number of tracks associated to jets misidentified as τ candidates is found to be poorly modelled in simulation. Events in the data tend to have fewer τ candidates with one or three tracks (this explains the differences between data and simulation in figure 1). In order to correct the τ candidate selection efficiencies in simulation, τ track multiplicity scale factors are derived using OS-SS events fulfilling the $W + {>}2$ jets selection, and are then applied to all jets misidentified as τ candidates in the simulation: 0.71 ± 0.03 for 1-track τ candidates; 0.92 ± 0.03 for 3-track τ candidates, where the errors are only statistical.

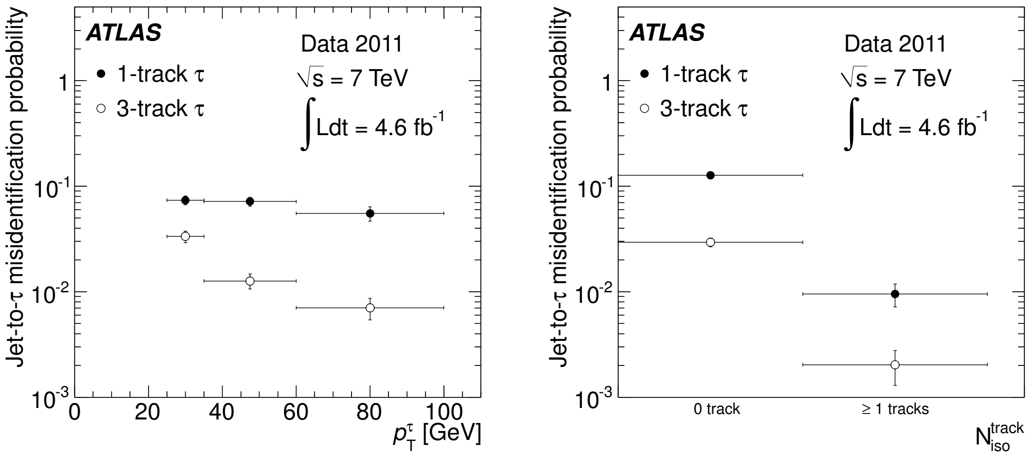
The probability for a light-quark jet to be misidentified as a τ jet is measured in the data and is binned in p_{T}^{τ}, the number of associated tracks $N_{\mathrm{track}}^{\tau}$ (one or three), and the number of tracks $N_{\mathrm{track}}^{\mathrm{iso}}$ found within $0.2 < \Delta R < 0.4$ of the τ candidate. For each bin, the jet $\to \tau_{\mathrm{had}}$ misidentification probability is defined as the number of objects passing the τ identification based on the likelihood criterion divided by the number prior to requiring identification. OS events are given a weight $+1$ and SS events are given a weight -1, in both the numerator and denominator of the jet $\to \tau_{\mathrm{had}}$ misidentification probability. After OS-SS subtraction, the selected events mostly contain τ candidates coming from light-quark jets and, to a much lesser extent, electrons, muons, and true hadronically decaying τ leptons. Figure 2 shows the measured values of the jet $\to \tau_{\mathrm{had}}$ misidentification probability in $W + {>}2$ jets events selected from the data, after OS-SS subtraction. These are used to scale all simulated events in the signal region. Events fulfilling the requirements listed in the beginning of this section, in which the selected τ object originates from a jet (of any type), are weighted by the misidentification probabilities. An additional weighting factor ($+1$ for OS events and -1 for SS events) is then used to perform the OS-SS subtraction.

[6] The leading process in this control region is $gq \to Wq'$.



(a) (b)

Figure 1. Distributions of the transverse mass m_{T} for events fulfilling the W + >2 jets selection, without the requirement $m_{\mathrm{T}} > 30$ GeV. Each colour corresponds to a type of generator-level particle matched to a τ candidate (i.e. the highest energy particle within a cone of radius $\Delta R = 0.2$ around the τ candidate is considered). The SS events are (a) given a weight of -1 and (b) subtracted from the OS events. All simulated SM processes are considered.



(a) (b)

Figure 2. Probability for a light-quark jet to be misidentified as a 1-track or 3-track τ jet, measured in a region enriched with OS-SS W + >2 jets events in the data, as a function of (a) p_{T}^{τ} and (b) the number of tracks $N_{\mathrm{track}}^{\mathrm{iso}}$ found within $0.2 < \Delta R < 0.4$ of the τ jet.

4 Results

4.1 Computation of event yield ratios

For each of the four final states considered here ($e + \tau_{\mathrm{had}}$, $e + \mu$, $\mu + \tau_{\mathrm{had}}$ and $\mu + e$), the OS-SS event yield $\mathcal{N}$ can be split into two contributions: from $t\bar{t}$ events (where the top quarks may decay into both bW and bH^+) and from all other SM processes except $t\bar{t} \to b\bar{b}W^+W^-$. The contributions from $t\bar{t}$ events are expressed as a function of the

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cross section $\sigma_{t\bar{t}}$, the integrated luminosity $\mathcal{L}$, the branching fraction $B \equiv \mathcal{B}(t \to bH^+)$, as well as the selection efficiencies $\epsilon_{W^+W^-}$, $\epsilon_{H^+W^-}$, $\epsilon_{H^-W^+}$ and $\epsilon_{H^+H^-}$ for, respectively, $t\bar{t} \to b\bar{b}W^+W^-$, $t\bar{t} \to b\bar{b}H^+W^-$, $t\bar{t} \to b\bar{b}H^-W^+$ and $t\bar{t} \to b\bar{b}H^+H^-$ events, in each of the four final states considered here:

$$\begin{aligned}\mathcal{N} = \sigma_{t\bar{t}} \times \mathcal{L} \times \left[(1-B)^2\epsilon_{W^+W^-} + B(1-B)\left(\epsilon_{H^+W^-} + \epsilon_{H^-W^+}\right) + B^2\epsilon_{H^+H^-}\right] \\ +\mathcal{N}_{\text{Others}} \,. \end{aligned} \tag{4.1}$$

In turn, event yield ratios are defined as:

$$R_e = \frac{\mathcal{N}(e+\tau_{\text{had}})}{\mathcal{N}(e+\mu)} \quad \text{and} \quad R_\mu = \frac{\mathcal{N}(\mu+\tau_{\text{had}})}{\mathcal{N}(\mu+e)}. \tag{4.2}$$

The event yields in the τ_{had}+lepton and dilepton final states are summarised in table 2 for the background-only hypothesis, as well as in the presence of a 130 GeV charged Higgs boson in the top quark decay. The predicted values in the SM-only hypothesis and the measured values of the ratios R_e and R_μ are summarised in table 3. Note that the event yields for dilepton final states become smaller in the presence of a charged Higgs boson in top quark decays, despite the fact that a τ lepton decays into an electron or muon more often than a W boson. This results from the fact that electrons and muons produced in the decay chain $t \to bH^+ \to b\tau\nu \to bl + N\nu$ are, on average, softer than those coming from $t \to bW \to bl + N\nu$.

Figure 3 shows the variation of the event yields $\mathcal{N}(e+\tau_{\text{had}})$, $\mathcal{N}(e+\mu)$, $\mathcal{N}(\mu+\tau_{\text{had}})$ and $\mathcal{N}(\mu+e)$ with $\mathcal{B}(t \to bH^+)$, for a charged Higgs boson mass of 130 GeV. The presence of $H^+ \to \tau\nu$ in a fraction of the top quark decays leads to an increase of the number of $t\bar{t}$ events with a lepton and a τ jet. In combination with a small decrease of the number of dilepton $t\bar{t}$ events, this leads to an increase of the ratios R_e and R_μ. The sensitivity of this analysis to charged Higgs bosons is determined by the rate at which the ratios R_e and R_μ change with $\mathcal{B}(t \to bH^+)$, which depends on the selection efficiencies $\epsilon_{H^+W^-}$, $\epsilon_{H^-W^+}$, $\epsilon_{H^+H^-}$ and, in turn, on the charged Higgs boson mass. For $m_{H^+} = 150\,(160)$ GeV, the rate at which the ratios R_e and R_μ change with $\mathcal{B}(t \to bH^+)$ is found to be two (five) times smaller than for $m_{H^+} = 130$ GeV. Indeed, the selection efficiencies $\epsilon_{H^+W^-}$, $\epsilon_{H^-W^+}$, $\epsilon_{H^+H^-}$ are reduced for m_{H^+} values in the vicinity of m_{top}, because the b-jet arising from $t \to bH^+$ becomes softer when the mass difference $m_{\text{top}} - m_{H^+}$ is smaller.

4.2 Systematic uncertainties

Systematic uncertainties arise from the simulation of the electron and muon triggers, from the reconstruction and identification efficiencies of the physics objects, as well as from the energy/momentum scale and resolution for these objects. In order to assess their impact, the selection cuts of this analysis are re-applied after shifting a particular parameter by its ± 1 standard deviation uncertainty, while other parameters are fixed. The largest instrumental systematic uncertainties are for jets. In comparison, the systematic uncertainties arising from the reconstruction and identification of electrons, muons and τ jets are small. All instrumental systematic uncertainties are propagated to the reconstructed $E_{\text{T}}^{\text{miss}}$.

Sample	OS-SS event yields	
	$e + \tau_{\text{had}}$	$e + \mu$
Misidentified electrons or muons	-0.8 ± 3.0	94 ± 37
W/Z+jets & diboson	2.1 ± 0.9	0.7 ± 0.4
Single top quark	3.3 ± 0.8	24 ± 4
$t\bar{t}$	111 ± 25	980 ± 200
$\sum$ SM	116 ± 25	1100 ± 210
Data	144	1247
$t\bar{t}$ with $t \to bH^+$ (130 GeV)	30 ± 4	27 ± 4
Prediction with signal	139 ± 28	1070 ± 200
	$\mu + \tau_{\text{had}}$	$\mu + e$
Misidentified electrons or muons	0.2 ± 1.0	74 ± 37
W/Z+jets & diboson	2.6 ± 1.6	0.7 ± 0.4
Single top quark	4.6 ± 0.9	18 ± 3
$t\bar{t}$	131 ± 28	740 ± 150
$\sum$ SM	138 ± 29	830 ± 160
Data	153	929
$t\bar{t}$ with $t \to bH^+$ (130 GeV)	35 ± 4	20 ± 3
Prediction with signal	166 ± 32	810 ± 150

Table 2. Expected OS-SS event yields after all selection cuts in τ_{had}+lepton and dilepton channels, compared with 4.6 fb^{-1} of ATLAS data. The numbers shown for a hypothetical 130 GeV H^+ signal correspond to $\mathcal{B}(t \to bH^+) = 3\%$. The contribution of $t\bar{t} \to b\bar{b}WW$ events to the background is scaled accordingly. Statistical and systematic uncertainties are combined.

Ratio	R_e	R_μ
SM value	0.105 ± 0.012	0.166 ± 0.017
Measured value	0.115 ± 0.010 (stat)	0.165 ± 0.015 (stat)

Table 3. Predicted (in the SM-only hypothesis) and measured values of the event yield ratios R_e and R_μ. For the values of the ratios predicted using simulation, the statistical and systematic uncertainties are combined.

The $t\bar{t}$ cross section used in this analysis is $\sigma_{t\bar{t}} = 167^{+17}_{-18}$ pb [26]. To estimate systematic uncertainties arising from the $t\bar{t}$ generation and the parton shower model, the acceptance is computed for $t\bar{t}$ events produced with either MC@NLO interfaced to HERWIG and JIMMY [37] for the hadronisation and the underlying event, or POWHEG [38] interfaced to PYTHIA. Systematic uncertainties on initial- and final-state radiation are computed using $t\bar{t}$ samples generated with AcerMC interfaced to PYTHIA, where the relevant parameters in PYTHIA are varied in a range given by current experimental data [39]. These systematic uncertainties are dominated by the difference in modelling the numbers of tracks N^{τ}_{track} and $N^{\text{iso}}_{\text{track}}$ in, respectively, the core and isolation regions of the jets misidentified as τ

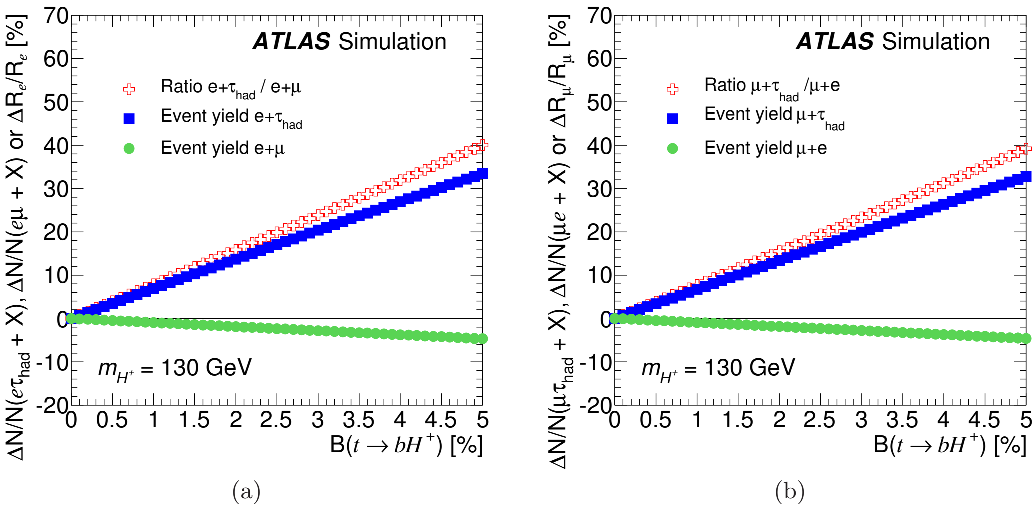

Figure 3. Relative variation with $\mathcal{B}(t \to bH^+)$ of (a) the event yields $\mathcal{N}(e + \tau_{\rm had})$, $\mathcal{N}(e + \mu)$ and their ratio, as well as (b) $\mathcal{N}(\mu + \tau_{\rm had})$, $\mathcal{N}(\mu + e)$ and their ratio, assuming the presence of a 130 GeV charged Higgs boson in $t\bar{t}$ events.

candidates. The various simulated $t\bar{t}$ samples are reweighted so that the $N^{\tau}_{\rm track}$ and the $N^{\rm iso}_{\rm track}$ distributions match[7] before the systematic uncertainties on the $t\bar{t}$ generation, the parton shower model, as well as initial- and final-state radiation, are evaluated.

For the signal samples, which are generated with PYTHIA (i.e. without higher-order corrections), no alternative generator is available, hence the systematic uncertainty is set to the relative difference in acceptance between $t\bar{t}$ events generated with MC@NLO interfaced to HERWIG/JIMMY and with AcerMC, which is also a leading-order generator, interfaced to PYTHIA. For the systematic uncertainty coming from initial- and final-state radiation, the same simulated samples as for the SM $t\bar{t}$ events are used. In the evaluation of the systematic uncertainties for the signal samples, only τ jets matched to true hadronically decaying τ leptons in the generated events are considered.

For the backgrounds with misidentified leptons, the largest systematic uncertainties arise from the sample dependence: the misidentification probabilities are calculated in a control region dominated by gluon-initiated events, but later used in a data sample with a higher fraction of quark-initiated events. The total systematic uncertainty on the backgrounds with misidentified leptons is 38% for electron-triggered events and 49% for muon-triggered events. It corresponds to the relative variation of the number of events with exactly one trigger-matched lepton and two jets, after having considered all systematic uncertainties. The requirement of having two b-jets in the event does not have a significant impact on these systematic uncertainties and neither does the presence of a second lepton.

For the estimation of backgrounds with jets misidentified as hadronically decaying τ leptons, the systematic uncertainty on the scale factors associated with the number of tracks is determined by varying the requirement on the jet multiplicity and the magnitude of the subtraction of τ candidates matched to a true electron, muon or τ lepton in the

[7]Both variables are reweigthed in a correlated way.

generated events. This uncertainty is 7% for 1-track τ jets and 11% for 3-track τ jets. In addition, systematic uncertainties on the jet $\to \tau_{\text{had}}$ misidentification probability arise from statistical uncertainties due to the limited control sample size, the differences between misidentification probabilities computed in the region enriched with W + >2 jets events and the signal region, as well as the small contamination from true τ leptons (including those possibly coming from $H^+ \to \tau\nu$) in the region enriched with W + >2 jets events.

Some of the systematic uncertainties above affect the τ_{had}+lepton and dilepton event yields in the same manner and, as a result, have a limited impact on R_e and R_μ. Systematic uncertainties arising from jets and $E_{\text{T}}^{\text{miss}}$ are common to all reconstructed events in the simulation, hence they should cancel in the ratios R_e and R_μ. However, due to the use of data-driven background estimates and because of the removal of geometric overlaps between reconstructed objects, some of these systematic uncertainties still have a minor impact. In the EL (MU) category, the systematic uncertainties related to the trigger-matched electron (muon) are the same for the $e + \tau_{\text{had}}$ and $e + \mu$ ($\mu + \tau_{\text{had}}$ and $\mu + e$) events, thereby not affecting the predicted value of the ratio R_e (R_μ). Those coming from the reconstructed muon (electron) only affect event yields in the denominator, and hence the ratio. Similarly, the systematic uncertainties coming from the τ jets and their misidentification probabilities only affect the numerator of R_e and R_μ, hence they do have an impact on the analysis. This is also the case for systematic uncertainties on the backgrounds with misidentified leptons, which have a larger contribution in the dilepton events, i.e. on the denominator of R_e and R_μ. Table 4 shows how these ratios (in the SM-only hypothesis) change when shifting a particular parameter by its ±1 standard deviation uncertainty.

4.3 Exclusion limits

To test the compatibility of the data with the background-only or the signal+background hypotheses, a profile likelihood ratio [40] is used with R_e and R_μ as the discriminating variables. The systematic uncertainties are incorporated via nuisance parameters, and the one-sided profile likelihood ratio, $\tilde{q}_\mu$, is used as a test statistic. No significant deviation from the SM prediction is observed in 4.6 fb^{-1} of data. Exclusion limits are set on the branching fraction $\mathcal{B}(t \to bH^+)$ by rejecting the signal hypothesis at the 95% confidence level (CL) using the CL_s procedure [41]. These limits are based on the asymptotic distribution of the test statistic [40]. They are first set for electron-triggered and muon-triggered events separately (see figure 4), and then using a global event yield ratio $R_{e+\mu}$ defined as:

$$R_{e+\mu} = \frac{\mathcal{N}(e + \tau_{\text{had}}) + \mathcal{N}(\mu + \tau_{\text{had}})}{\mathcal{N}(e + \mu) + \mathcal{N}_{\text{OR}}(\mu + e)}, \tag{4.3}$$

where $\mathcal{N}_{\text{OR}}(\mu + e)$ is the event yield in the $\mu + e$ channel after removing the dilepton events that simultaneously fire a single-electron trigger and a single-muon trigger, as those already appear in $\mathcal{N}(e + \mu)$. The fraction of dilepton events common to the $\mu + e$ and $e + \mu$ final states is about 42% in the data. Using this global event yield ratio, upper limits in the range 3.2%–4.4% can be placed on $\mathcal{B}(t \to bH^+)$ for charged Higgs boson masses in the range 90–140 GeV, as shown in figure 5 and table 5.

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Systematic uncertainty	ΔR_e	ΔR_μ
Integrated luminosity	0.3%	0.3%
Electron trigger efficiency	0.1%	N/A
Electron reco. and ID efficiencies	0.2%	1.9%
Electron energy resolution	0.1%	<0.1%
Electron energy scale	0.1%	0.3%
Muon trigger efficiency	N/A	0.1%
Muon reco. and ID efficiencies	1.0%	0.1%
Muon momentum resolution	<0.1%	<0.1%
Muon momentum scale	0.1%	<0.1%
τ ID efficiency	3.9%	3.9%
τ energy scale	2.9%	3.0%
τ mis-ID (data-driven): number of associated tracks	2.1%	2.1%
τ mis-ID (data-driven): true τ_{had} contamination	0.2%	0.2%
τ mis-ID (data-driven): H^+ signal contamination	0.6%	0.6%
τ mis-ID (data-driven): event environment	1.3%	1.2%
τ mis-ID (data-driven): statistical uncertainties	3.3%	3.2%
τ mis-ID (data-driven): electron veto uncertainties	0.6%	0.3%
b-tagging	1.9%	2.3%
Jet vertex fraction	0.1%	0.4%
Jet energy resolution	0.4%	<0.1%
Jet energy scale	0.7%	0.5%
Jet reconstruction efficiency	0.1%	0.4%
$E_{\text{T}}^{\text{miss}}$	0.3%	0.1%
$t\bar{t}$: cross section	0.7%	0.6%
$t\bar{t}$: generator and parton shower	5.7%	4.4%
$t\bar{t}$: initial- and final-state radiation	3.6%	3.7%
Backgrounds with misidentified leptons	3.5%	4.3%
Total (added in quadrature)	10.3%	10.1%

Table 4. Relative variation of the ratios R_e and R_μ in the SM-only hypothesis after shifting a particular parameter by its ± 1 standard deviation uncertainty.

m_{H^+} (GeV)	90	100	110	120	130	140	150	160
95% CL observed (expected) limit on $\mathcal{B}(t \to bH^+)$ using the ratio $R_{e+\mu}$	3.3% (3.1%)	3.6% (3.3%)	3.2% (3.0%)	3.4% (3.1%)	3.6% (3.3%)	4.4% (4.0%)	7.3% (6.7%)	18.3% (16.8%)

Table 5. Observed (expected) 95% CL upper limits on $\mathcal{B}(t \to bH^+)$ derived from the event yield ratio $R_{e+\mu}$, as a function of the charged Higgs boson mass, obtained for an integrated luminosity of $4.6\,\text{fb}^{-1}$ and with the assumption that $\mathcal{B}(H^+ \to \tau\nu) = 1$.

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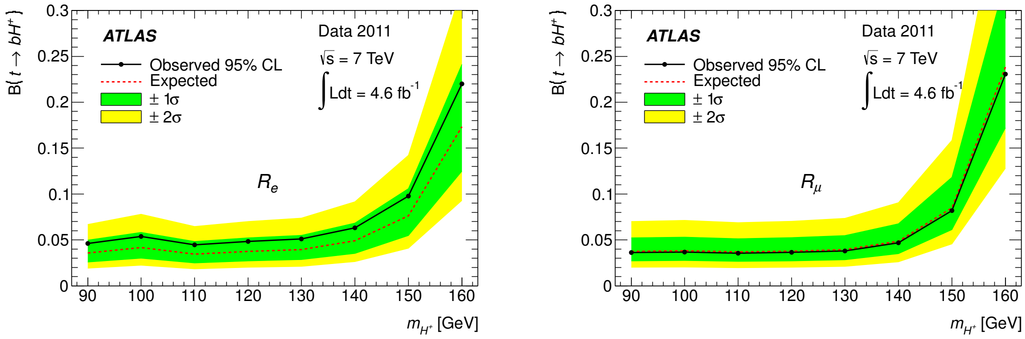

(a) Using R_e (b) Using R_μ

Figure 4. Upper limits on $\mathcal{B}(t \to bH^+)$ derived from the event yield ratios (a) R_e and (b) R_μ, as a function of the charged Higgs boson mass, obtained for an integrated luminosity of 4.6 fb^{-1} and with the assumption $\mathcal{B}(H^+ \to \tau\nu) = 1$. The solid line in the figure is used to denote the observed 95% CL upper limits, while the dashed line represents the expected exclusion limits. The green and yellow regions show the 1σ and 2σ error bands.

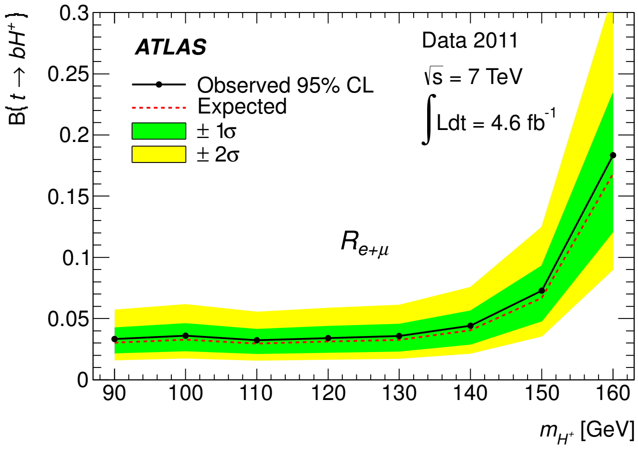

Figure 5. Upper limits on $\mathcal{B}(t \to bH^+)$ derived from the event yield ratio $R_{e+\mu}$, as a function of the charged Higgs boson mass, obtained for an integrated luminosity of 4.6 fb^{-1} and with the assumption $\mathcal{B}(H^+ \to \tau\nu) = 1$. The solid line in the figure is used to denote the observed 95% CL upper limits, while the dashed line represents the expected exclusion limits. The green and yellow regions show the 1σ and 2σ error bands.

In a previously published search for charged Higgs bosons [8], based on the data collected in 2011 with ATLAS, upper limits on $\mathcal{B}(t \to bH^+)$ were derived using various distributions of discriminating variables in $\tau_{\rm had}$+jets, $\tau_{\rm had}$+lepton and lepton+jets final states. The most sensitive channel was $\tau_{\rm had}$+jets, except for low values of m_{H^+}. A new set of combined upper limits on $\mathcal{B}(t \to bH^+)$ is derived, using the transverse mass distribution of $\tau_{\rm had}$+jets events from ref. [8] and the global event yield ratio $R_{e+\mu}$, as shown in figure 6 and table 6. Since a lepton veto is applied for charged Higgs boson searches in $\tau_{\rm had}$+jets final states, there is no correlation between such events and those selected in this study to determine the event yield ratios. With this combination of upper limits, charged Higgs bosons can be excluded for values of the branching fraction $\mathcal{B}(t \to bH^+)$ larger than

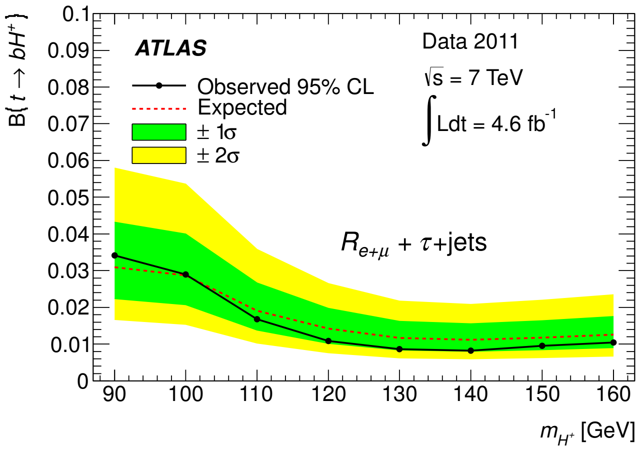

Figure 6. Upper limits on $\mathcal{B}(t \to bH^+)$ derived from the transverse mass distribution of $\tau_{\rm had}$+jets events in ref. [8] and the event yield ratio $R_{e+\mu}$, as a function of the charged Higgs boson mass, obtained for an integrated luminosity of 4.6 fb^{-1} and with the assumption $\mathcal{B}(H^+ \to \tau\nu) = 1$. The solid line in the figure is used to denote the observed 95% CL upper limits, while the dashed line represents the expected exclusion limits. The green and yellow regions show the 1σ and 2σ error bands.

m_{H^+} (GeV)	90	100	110	120	130	140	150	160
95% CL observed (expected) limit on $\mathcal{B}(t \to bH^+)$ using $R_{e+\mu}$ and $\tau_{\rm had}$+jets	3.4% (3.1%)	2.9% (2.8%)	1.7% (1.9%)	1.1% (1.4%)	0.9% (1.2%)	0.8% (1.1%)	1.0% (1.2%)	1.1% (1.2%)
95% CL observed (expected) limit in ref. [8]	4.8% (4.2%)	3.4% (3.5%)	2.1% (2.5%)	1.3% (1.9%)	1.1% (1.5%)	1.0% (1.3%)	1.1% (1.2%)	1.0% (1.3%)

Table 6. Observed (expected) 95% CL upper limits on $\mathcal{B}(t \to bH^+)$ derived using $\tau_{\rm had}$+jets events in ref. [8] and the ratio $R_{e+\mu}$, as a function of the charged Higgs boson mass, obtained for an integrated luminosity of 4.6 fb^{-1} and assuming that $\mathcal{B}(H^+ \to \tau\nu) = 1$. The exclusion limits published in ref. [8] are also shown for comparison purposes.

0.8% to 3.4%, for m_{H^+} between 90 GeV and 160 GeV. These exclusion limits represent an improvement with respect to those published in ref. [8].

In figure 7, the combined limit on $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to \tau\nu)$ is interpreted in the context of the $m_h^{\rm max}$ scenario [11] of the MSSM. The following relative theoretical uncertainties on $\mathcal{B}(t \to bH^+)$ are considered [42, 43]: 5% for one-loop electroweak corrections missing from the calculations, 2% for missing two-loop QCD corrections, and about 1% (depending on $\tan\beta$) for Δ_b-induced uncertainties, where Δ_b is a correction factor for the running b-quark mass [44]. These uncertainties are added linearly, as recommended by the LHC Higgs cross-section working group [43].

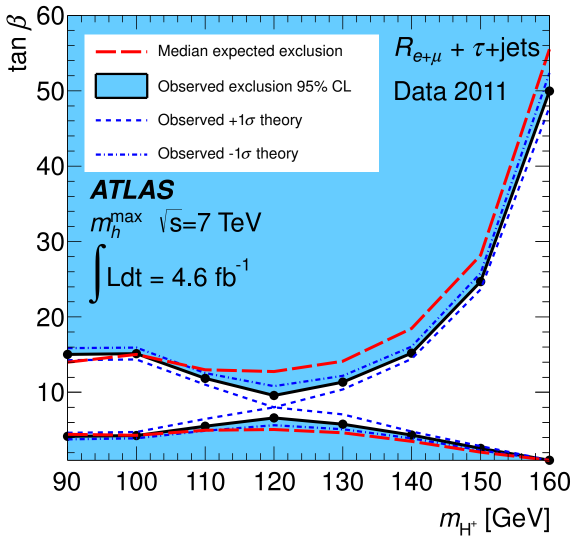

Figure 7. Limits for charged Higgs boson production from top quark decays in the m_{H^+}-$\tan\beta$ plane, derived using $\tau_{\rm had}$+jets events in ref. [8] and the ratio $R_{e+\mu}$, in the context of the $m_h^{\rm max}$ scenario of the MSSM. The 1σ band around the observed limit (dashed lines) 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.

Assuming that the boson recently discovered at the LHC [45, 46] is one of the neutral MSSM Higgs bosons, only a certain region in the m_{H^+}-$\tan\beta$ plane is still allowed for a given scenario [47]. If the new boson is the lightest neutral MSSM Higgs boson (h^0), it would imply $\tan\beta > 3$ and $m_{H^+} > 155$ GeV. However, the allowed region depends strongly on MSSM parameters which, on the other hand, do not affect the charged Higgs boson production and decay significantly. Thus, by adjusting these MSSM parameters, the region in which the Higgs boson mass can take a value of about 125 GeV can be changed significantly, while the ATLAS exclusion region shown here is relatively stable with respect to these changes. Should the recently discovered boson instead be the heavier CP-even Higgs boson (H^0), the additional constraint from $m_{H^0} \simeq 125$ GeV only leads to an upper limit of roughly $m_{H^+} < 150$ GeV, with suppressed couplings for h^0. If the recently discovered particle is an MSSM Higgs boson, excluding a low-mass charged Higgs boson would thus imply that it is the lightest neutral state h^0.

5 Conclusions

Charged Higgs bosons have been searched for in $t\bar{t}$ events, in the decay mode $t \to bH^+$ followed by $H^+ \to \tau\nu$. A total of 4.6 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV, recorded in 2011 with the ATLAS experiment at the LHC, is used. Event yield ratios are measured in the data and compared to the predictions from simulations, between electron-triggered $e + \tau_{\rm had}$ and $e + \mu$ events, and between muon-triggered $\mu + \tau_{\rm had}$ and $\mu + e$ events, in order to search for a violation of lepton universality in $t\bar{t}$ events. This method reduces the impact of several systematic uncertainties in the analysis. Data-driven methods and

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simulation are employed to estimate the number of background events. The observed data are found to be in agreement with the SM predictions. Assuming $\mathcal{B}(H^+ \to \tau\nu) = 100\%$, upper limits at the 95% confidence level in the range 3.2%–4.4% have been placed on the branching fraction $\mathcal{B}(t \to bH^+)$ for charged Higgs boson masses in the range 90–140 GeV. For charged Higgs boson masses below 110 GeV, this analysis improves the previously published limits on $\mathcal{B}(t \to bH^+)$, based on direct searches for charged Higgs bosons in $t\bar{t}$ decays using the lepton+jets, τ_{had}+jets and τ_{had}+lepton final states. When the results of the present analysis are combined with the results from the search for charged Higgs bosons in $t\bar{t}$ decays using the τ_{had}+jets final state [8], upper limits on $\mathcal{B}(t \to bH^+)$ are set in the range 0.8%–3.4%, for m_{H^+} between 90 GeV and 160 GeV.

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