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Search for charged Higgs bosons produced in association with a top quark and decaying via $H^{\pm} \to \tau\nu$ using pp collision data recorded at $\sqrt{s} = 13$ TeV by the ATLAS detector

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ABSTRACT

Charged Higgs bosons produced in association with a single top quark and decaying via $H^{\pm} \to \tau\nu$ are searched for with the ATLAS experiment at the LHC, using proton–proton collision data at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 3.2 fb^{-1}. The final state is characterised by the presence of a hadronic τ decay and missing transverse momentum, as well as a hadronically decaying top quark, resulting in the absence of high-transverse-momentum electrons and muons. The data are found to be consistent with the expected background from Standard Model processes. A statistical analysis leads to 95% confidence-level upper limits on the production cross section times branching fraction, $\sigma(pp \to [b]tH^{\pm}) \times \mathrm{BR}(H^{\pm} \to \tau\nu)$, between 1.9 pb and 15 fb, for charged Higgs boson masses ranging from 200 to 2000 GeV. The exclusion limits for this search surpass those obtained with the proton–proton collision data recorded at $\sqrt{s} = 8$ TeV.

1. Introduction

Following the discovery of a neutral scalar particle at the Large Hadron Collider (LHC) in 2012 [1,2], an important question is whether this new particle is the Higgs boson of the Standard Model (SM) or part of an extended Higgs sector. Charged Higgs bosons[1] appear in several non-minimal scalar sectors, where a second doublet [3] or triplets [4–8] are added to the SM Higgs doublet. The observation of a charged Higgs boson would therefore clearly indicate physics beyond the SM.

The ATLAS and CMS collaborations have searched for light charged Higgs bosons, produced in top-quark decays, using proton–proton (pp) collisions at $\sqrt{s} = 7$–8 TeV in the $\tau\nu$ [9–13] and cs [14,15] decay modes. Using data collected at $\sqrt{s} = 8$ TeV, charged Higgs bosons heavier than the top quark were also searched for, using final states originating from both the $\tau\nu$ and tb decay modes [11,13,16]. Vector-boson-fusion H^+ production was also searched for by ATLAS using the WZ final state [17]. No evidence of a charged Higgs boson was found in any of these searches.

For m_{H^+} greater than the top-quark mass m_{top}, which is the mass range of interest in this paper, the main production mode

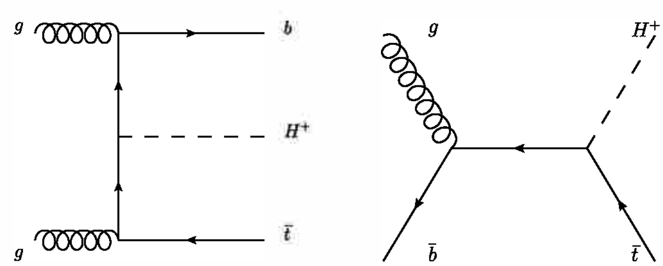

Fig. 1. Leading-order Feynman diagrams for the production of a charged Higgs boson with a mass $m_{H^+} > m_{\mathrm{top}}$, in association with a single top quark (left in the 4FS, and right in the 5FS).

of a charged Higgs boson at the LHC is expected to be in association with a top quark [18–20]. The corresponding Feynman diagrams are shown in Fig. 1. When calculating the corresponding cross section in a four-flavour scheme (4FS), b-quarks are dynamically produced, whereas in a five-flavour scheme (5FS), the b-quark is also considered as an active flavour in the proton. For model-dependent interpretations, 4FS and 5FS cross sections are averaged according to Ref. [21]. In two-Higgs-doublet models (2HDMs), the production and decay of the charged Higgs boson also depend on the parameter $\tan\beta$, defined as the ratio of the vacuum expectation values of the two Higgs doublets, and the mixing angle α between the CP-even Higgs bosons. In the alignment limit, where $\cos(\beta - \alpha) \simeq 0$, the decay $H^+ \to \tau\nu$ can have a substantial branch-

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[1] In the following, charged Higgs bosons are denoted H^+, with the charge-conjugate H^- always implied. Similarly, generic symbols are used for their decay products.

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ing fraction. In a type-II 2HDM, even when the decay $H^+ \to tb$ dominates, the branching fraction BR($H^+ \to \tau\nu$) can reach 10–15% at large values of $\tan\beta$ [22].

This paper describes a search for charged Higgs bosons in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment. The production of a charged Higgs boson in association with a single top quark and its decay via $H^+ \to \tau\nu$ are explored in the mass range 200 to 2000 GeV, extending by 1000 GeV the mass range considered by the ATLAS collaboration during Run 1 of the LHC. The final state is characterised by the presence of a hadronic τ decay and missing transverse momentum arising from the H^+ decay, as well as a fully hadronic top-quark decay, resulting in the absence of high-transverse-momentum electrons and muons. The SM prediction is compared to the data, and results for the signal cross section times branching fraction $\sigma(pp \to [b]tH^\pm) \times \mathrm{BR}(H^\pm \to \tau\nu)$ are presented, together with an interpretation in the hMSSM benchmark scenario [23,24], in which the light CP-even Higgs boson mass m_h is set to 125 GeV, without choosing explicitly the soft-supersymmetry-breaking parameters.

2. Data and simulated events

The ATLAS experiment [25] consists of an inner detector with coverage in pseudorapidity[2] up to $|\eta| = 2.5$, surrounded by a thin 2 T superconducting solenoid, a calorimeter system extending up to $|\eta| = 4.9$ and a muon spectrometer extending up to $|\eta| = 2.7$ that measures the deflection of muon trajectories in the field of three superconducting toroid magnets. The innermost pixel layer, the insertable B-layer (IBL), was added between the first and second runs of the LHC, around a new, narrower and thinner beam pipe [26]. A two-level trigger system is used to select events of interest [27]. The integrated luminosity, considering only the data-taking periods of 2015 in which all relevant detector subsystems were operational, is 3.2 fb^{-1} and has an uncertainty of 5%. It is derived following a methodology similar to that detailed in Ref. [28], from a calibration of the luminosity scale using x–y beam-separation scans performed in August 2015.

Simulated events of H^+ production in association with a single top quark are generated in the 4FS at the next-to-leading order (NLO) with MadGraph5_aMC@NLO v.2.2.2 [29] using the NNPDF23LO [30] parton distribution function (PDF) set, interfaced to Pythia v8.186 [31] with the A14 set of tuned parameters (tune) [32] for the underlying event.

The main backgrounds are the production of $t\bar{t}$ pairs, single top quarks, W+jets, Z/γ^*+jets and electroweak gauge boson pairs ($WW/WZ/ZZ$), as well as multi-jet events. For the generation of $t\bar{t}$ pairs and single top quarks in the Wt- and s-channels, the Powheg-Box v2 [33,34] generator with the CT10 [35,36] PDF set in the matrix-element calculations is used. Electroweak t-channel single-top-quark events are generated using the Powheg-Box v1 generator. This generator uses the 4FS for the NLO matrix-element calculations together with the fixed four-flavour PDF set CT10F4. For this process, the top quark is decayed using MadSpin [37], thereby preserving all spin correlations. For all backgrounds above, the parton shower, the fragmentation and the underlying event are simulated using Pythia v6.428 [38] with the CTEQ6L1 [39] PDF set and the corresponding Perugia 2012 (P2012) tune [40]. The top-quark mass is set to 172.5 GeV for all relevant background and signal samples. The $t\bar{t}$ cross section is calculated at next-to-next-to-leading order (NNLO), including soft-gluon resummation to the next-to-next-to-leading logarithmic (NNLL) order, with Top++ v2.0 [41–47]. The single-top-quark samples are normalised to the approximate NNLO cross sections [48–50]. Events containing a W or Z boson with associated jets are simulated using MadGraph5_aMC@NLO v.2.2.2 at LO with the NNPDF23LO PDF set, interfaced to Pythia v8.186 with the A14 underlying-event tune. These samples are normalised to the NNLO cross sections calculated with FEWZ [51–53]. Finally, diboson processes are simulated using the Powheg-Box v2 generator interfaced to the Pythia v8.186 parton shower model. The CT10 NLO set is used as the PDF for the hard-scatter process, while the CTEQ6L1 PDF set is used for the parton shower. The non-perturbative effects are modelled using the AZNLO tune [54]. The diboson samples are normalised to their NLO cross sections, as computed by the event generator.

Whenever applicable, Photos++ v3.52 [55] is employed for photon radiation from charged leptons, and EvtGen v1.2.0 [56] is used to simulate b- and c-hadron decays. Multiple overlaid pp collisions (pile-up, with 14 collisions per bunch-crossing on average) are simulated with the soft QCD processes of Pythia v8.186 using the MSTW2008LO [57–59] PDF set and the A2 underlying-event tune [60]. All simulated signal and background samples are processed through a simulation [61] of the detector geometry and response using Geant4 [62]. Finally, they are processed through the same reconstruction software as the data.

In the following, the backgrounds are categorised based on the type of reconstructed objects identified as the visible decay products[3] of the hadronically decaying τ candidate ($\tau_{\text{had-vis}}$). Only simulated events having a true hadronically decaying τ at generator level (τ_{had}) or with a charged lepton (electron or muon) misidentified as a $\tau_{\text{had-vis}}$ are kept. Backgrounds arising from a jet misidentified as a $\tau_{\text{had-vis}}$ are estimated with a data-driven method.

3. Object reconstruction and identification

In the ATLAS experiment, hadronic jets are reconstructed from energy deposits in the calorimeters, using the anti-k_t algorithm [63,64] with a radius parameter $R = 0.4$. In the following, jets are required to have a transverse momentum $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$. A multi-variate technique (Jet Vertex Tagger) relying on jet energy and tracking variables to determine the likelihood that a given jet originates from pile-up [65] is applied to jets with $p_{\mathrm{T}} < 50$ GeV and $|\eta| < 2.4$. Jets arising from b-hadron decays are identified by using an algorithm that combines impact parameter information with the explicit identification of secondary and tertiary vertices within the jet into a b-tagging score [66,67]. The minimal requirement imposed on the b-tagging score in this analysis corresponds to a 70% efficiency to tag a b-quark-initiated jet in $t\bar{t}$ events, with rejection rates of 400 for light-quark-initiated jets, 27 for τ_{had}-initiated jets and 8 for c-quark-initiated jets, enhanced with respect to Run 1 by the use of the IBL and an improved algorithm. The tagging efficiencies from simulation are corrected based on the results of flavour-tagging calibrations performed with data [68].

Candidates for identification as $\tau_{\text{had-vis}}$ arise from jets that have $p_{\mathrm{T}} > 10$ GeV and for which one or three charged-particle tracks are found within a cone of size[4] $\Delta R = 0.2$ around the axis of

[2] 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 upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

[3] This refers to all τ decay products except the neutrinos.

[4] $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where $\Delta\eta$ and $\Delta\phi$ are differences in pseudorapidity and azimuthal angle, respectively.

the $\tau_{\text{had-vis}}$ candidate [69,70]. These objects are further required to have a visible transverse momentum (p_{T}^{τ}) of at least 40 GeV and to be within $|\eta| < 2.3$. The output of boosted decision tree (BDT) algorithms [71] is used in order to distinguish $\tau_{\text{had-vis}}$ candidates from jets not initiated by hadronically decaying τ-leptons. This is done separately for decays with one or three charged-particle tracks, and for varying values of the identification efficiency. In this analysis, a working point corresponding to a 55% (40%) efficiency for the identification of 1-prong (3-prong) $\tau_{\text{had-vis}}$ objects is used, with rejection rates of $\mathcal{O}(10^2)$ for jets.

In this analysis, events with isolated electron or muon candidates with a transverse energy or momentum above 20 GeV are rejected. Electron candidates [72] are reconstructed from energy deposits (clusters) in the electromagnetic calorimeter, associated with a reconstructed track in the inner detector. The pseudorapidity range for the electromagnetic clusters covers the fiducial volume of the detector, $|\eta| < 2.47$ (the transition region between the barrel and end-cap calorimeters, $1.37 < |\eta| < 1.52$, is excluded). Quality requirements on the electromagnetic clusters and the tracks, as well as isolation requirements in a cone around the electron candidate based on its transverse energy and the tracking information, are then applied in order to reduce contamination from jets. The muon candidates are reconstructed from track segments in the muon spectrometer, and matched with tracks found in the inner detector within $|\eta| < 2.5$ [73]. The final muon candidates are refitted using the complete track information from both detector systems. They must fulfil quality requirements including a p_{T}-dependent track-based isolation requirement in a cone of variable size around the muon, which has good performance under high pile-up conditions and/or when a muon is close to a jet.

When objects overlap geometrically, the following procedures are applied, in this order. Every $\tau_{\text{had-vis}}$ candidate that overlaps with a loosely identified electron or muon, within a cone of size ΔR of 0.4 or 0.2, respectively, is removed. Then, reconstructed jets are discarded if an electron or a $\tau_{\text{had-vis}}$ candidate fulfilling the selection criteria above is found within a cone of size $\Delta R = 0.2$.

The magnitude $E_{\text{T}}^{\text{miss}}$ of the missing transverse momentum [74] is reconstructed from the negative vector sum of transverse momenta of reconstructed and fully calibrated objects (collected in the hard term), as well as from reconstructed tracks associated with the hard-scatter vertex which are not in the hard term (collected in the soft term). In order to mitigate the effects of pile-up, the $E_{\text{T}}^{\text{miss}}$ is refined by using object-level corrections for the identified electrons, muons, jets and $\tau_{\text{had-vis}}$ candidates in the hard term. As the soft term contains only tracks associated with the hard-scatter vertex, it is robust against pile-up.

4. Event selection and background modelling

Charged Higgs bosons are searched for in the topology $pp \to [b]tH^+ \to [b](jjb)(\tau_{\text{had}}\nu)$. Events collected using an $E_{\text{T}}^{\text{miss}}$ trigger with a threshold at 70 GeV are considered. After ensuring that no jets are consistent with having originated from instrumental effects or non-collision background, each event is required to contain one $\tau_{\text{had-vis}}$ with $p_{\text{T}}^{\tau} > 40$ GeV (only the highest-p_{T}^{τ} candidate must fulfil the identification criteria described in Section 3), three or more jets with $p_{\text{T}} > 25$ GeV, of which at least one is b-tagged, no electron or muon with a transverse energy or momentum above 20 GeV, and to have $E_{\text{T}}^{\text{miss}} > 150$ GeV. For the selected events, the transverse mass m_{T} of the $\tau_{\text{had-vis}}$ and $E_{\text{T}}^{\text{miss}}$ system is defined as:

$$m_{\text{T}} = \sqrt{2p_{\text{T}}^{\tau}E_{\text{T}}^{\text{miss}}(1 - \cos\Delta\phi_{\tau,\text{miss}})}, \tag{1}$$

where $\Delta\phi_{\tau,\text{miss}}$ is the azimuthal angle between the $\tau_{\text{had-vis}}$ and the direction of the missing transverse momentum. This discriminating variable takes values lower than the W boson mass for $W \to \tau\nu$ decays in background events and lower than the H^+ mass for signal events, in the absence of detector resolution effects. A requirement of $m_{\text{T}} > 50$ GeV is applied in order to reject events with mismeasured $E_{\text{T}}^{\text{miss}}$, where $\tau_{\text{had-vis}}$ is nearly aligned with the direction of the missing transverse momentum.

The $E_{\text{T}}^{\text{miss}}$ trigger efficiency is measured in data and then used to reweight the simulated events, rather than relying on the $E_{\text{T}}^{\text{miss}}$ trigger in the simulated samples. This measurement is performed in a control region of the data that is orthogonal to the signal region described above, while retaining as many similarities as possible. For this purpose, events passing a single-electron trigger with a transverse energy threshold at 24 GeV are considered and required to contain exactly one electron matched to the corresponding trigger object, exactly one $\tau_{\text{had-vis}}$ and two or more jets, of which at least one is b-tagged. Both the electron and the $\tau_{\text{had-vis}}$ fulfil loose identification criteria in order to improve the statistical precision, with little impact on the measured $E_{\text{T}}^{\text{miss}}$ turn-on curve.

The "jet $\to \tau_{\text{had-vis}}$" background includes multi-jet events and other processes where a quark- or gluon-initiated jet is reconstructed and selected as the $\tau_{\text{had-vis}}$ candidate. This background is estimated with a data-driven method that relies on the measurement of the rate at which jets are misidentified as $\tau_{\text{had-vis}}$, hereafter referred to as the fake factor (FF). For this purpose, a control region populated primarily with misidentified $\tau_{\text{had-vis}}$ candidates is defined by using the same requirements as for the signal region, except that $E_{\text{T}}^{\text{miss}} < 80$ GeV and that the number of b-tagged jets is zero. The FF is defined as the ratio of the number of misidentified $\tau_{\text{had-vis}}$ candidates fulfilling the nominal object selection to the number of misidentified $\tau_{\text{had-vis}}$ candidates satisfying an "anti-$\tau_{\text{had-vis}}$" selection. This anti-$\tau_{\text{had-vis}}$ selection is defined by inverting the $\tau_{\text{had-vis}}$ identification criteria while maintaining a loose requirement on the BDT output score, which selects the same kind of objects mimicking $\tau_{\text{had-vis}}$ candidates as those fulfilling the identification criteria. In order to account for differences between gluon-, light-quark- and b-quark-initiated jets, FFs are parameterised as functions of p_{T}, the type of τ_{had} decay via the measured number of charged and neutral particles (π^0) [70], and the b-tagging score, as illustrated in Fig. 2. For each type of τ_{had} decay, the threshold value for the b-tagging score of the $\tau_{\text{had-vis}}$ candidate is optimised to keep enough entries in each of the two bins, below and above the threshold. After correcting for $\tau_{\text{had-vis}}$ candidates not fulfilling the identification criteria but matching a true τ_{had} at generator level, the number of events with a misidentified $\tau_{\text{had-vis}}$ in the signal region ($N_{\text{fakes}}^{\tau_{\text{had-vis}}}$) is derived from the subset of anti-$\tau_{\text{had-vis}}$ candidates as follows:

$$N_{\text{fakes}}^{\tau_{\text{had-vis}}} = \sum_i N_{\text{anti-}\tau_{\text{had-vis}}}(i) \times \text{FF}(i), \tag{2}$$

where the index i refers to each bin in terms of p_{T}, type of τ_{had} decay and b-tagging score, in which the FF is evaluated.

Backgrounds arising from events in which an electron or muon is misidentified as a $\tau_{\text{had-vis}}$ only contribute at the level of 5% to the total background, with misidentified muons contributing about one order of magnitude less than misidentified electrons. These backgrounds are estimated with simulation and include contributions from $t\bar{t}$, single-top-quark, $W/Z+$jets and diboson processes. If an electron is misidentified as a $\tau_{\text{had-vis}}$, a correction factor is applied to the event in order to account for the misidentification rate measured in a $Z \to ee$ control region in data, where one electron is reconstructed as a $\tau_{\text{had-vis}}$. Charged leptons from in-flight decays in multi-jet events are accounted for in the misidentified jet $\to \tau_{\text{had-vis}}$ background estimate.

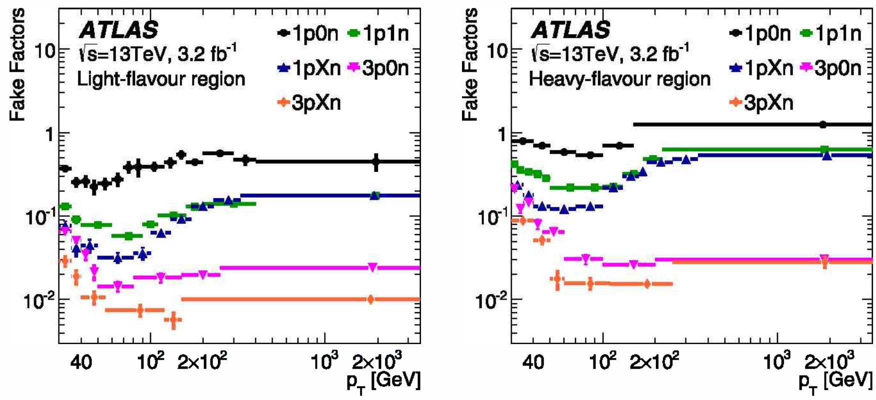

Fig. 2. Fake factors parameterised as a function of p_T and the reconstructed τ_{had} decay mode, for a b-tagging score of the $\tau_{had\text{-}vis}$ candidate below (left, light-flavour region) or above (right, heavy-flavour region) the chosen threshold. The τ_{had} decay mode is referred to as 1p0n, 1p1n, 1pXn, 3p0n or 3pXn, for a p-prong decay with n neutral particles (π^0), where X $\geq$ 2 (1) for 1pXn (3pXn) decays. The threshold value for the b-tagging score is set to keep enough entries in each of the two bins, separately for each type of τ_{had} decay. The errors shown arise from the statistical uncertainty for a given p_T bin.

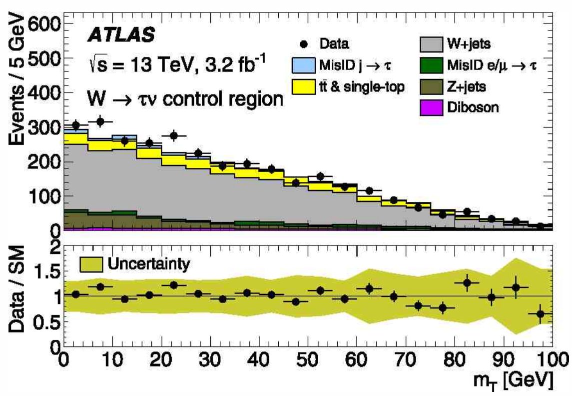

Fig. 3. Distribution of m_T in the control region enriched with $W \to \tau\nu$ events, which differs from the nominal event selection by the requirements that $m_T < 100$ GeV and that the number of b-tagged jets be zero. The $W \to \tau\nu$ background is normalised to the data through an overall scale factor. The total (statistical and systematic) uncertainties in the SM prediction are shown in the lower plot.

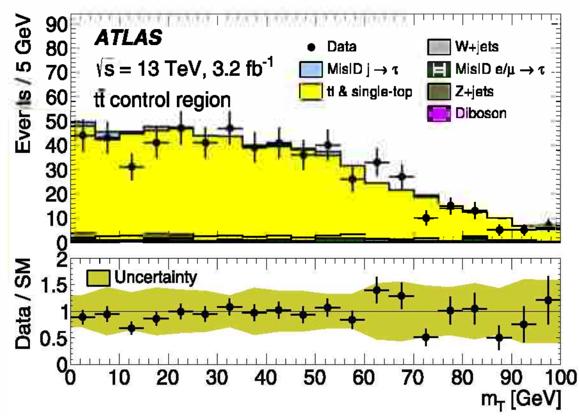

Fig. 4. Distribution of m_T in the control region enriched with $t\bar{t}$ events, which differs from the nominal event selection by the requirements that $m_T < 100$ GeV and that the number of b-tagged jets be at least two. The total (statistical and systematic) uncertainties in the SM prediction are shown in the lower plot.

The backgrounds with a true τ_{had} are estimated using simulation. The two dominant processes, $t\bar{t}$ and $W \to \tau\nu$, are validated in two dedicated control regions, which differ from the nominal event selection by the requirements that $m_T < 100$ GeV (instead of $m_T > 50$ GeV) and that the number of b-tagged jets be either at least two (for the control region enriched with $t\bar{t}$ events) or zero (for the control region enriched with $W \to \tau\nu$ events). The latter is also used to correct the overall normalisation of the simulated $W \to \tau\nu$ background. The m_T distributions that are predicted and measured in these two background-enriched control regions are displayed in Figs. 3 and 4. The relative signal contamination in the control region enriched in $W \to \tau\nu$ events is about two orders of magnitude smaller than the expected fraction of $H^+ \to \tau\nu$ events in the signal region. The control region enriched in $t\bar{t}$ events has a small overlap with the signal region, however the expected signal contamination is negligible, about one order of magnitude smaller than the expected fraction of $H^+ \to \tau\nu$ events in the signal region.

The expected number of background events in the signal region is shown in Table 1, together with the hypothetical contribution from charged Higgs bosons with a mass of 200 or 1000 GeV, and with $\sigma(pp \to [b]tH^\pm) \times \text{BR}(H^\pm \to \tau\nu)$ set to the prediction from the hMSSM scenario for $\tan\beta = 60$ (for a given mass, the expected signal yield increases quadratically with $\tan\beta$). The calculation of the production cross section is based on Refs. [22,75–78], while HDECAY [79] is used for computing the branching fraction. The signal acceptance at 200 (1000) GeV is 1.5% (12%), as evaluated with respect to simulated samples where both the τ-lepton and the associated top quark decay inclusively. The event yield observed in 3.2 fb^{-1} of data is also shown in Table 1 and found to be consistent with the expectation for the background-only hypothesis.

Table 1
Expected event yields for the backgrounds and a hypothetical H^+ signal after all selection criteria, and comparison with 3.2 fb^{-1} of data. The values shown for the signal assume a charged Higgs boson mass of 200 or 1000 GeV, with a cross section times branching fraction $\sigma(pp \to [b]tH^\pm) \times \text{BR}(H^\pm \to \tau\nu)$ corresponding to $\tan\beta = 60$ in the hMSSM benchmark scenario. The uncertainties include statistical and systematic components.

Sample	Event yield
True τ_{had}	
$t\bar{t}$ & single-top-quark	590 ± 170
$W \to \tau\nu$	58 ± 14
$Z \to \tau\tau$	6.4 ± 2.0
diboson (WW, WZ, ZZ)	4.3 ± 1.3
Misidentified $e, \mu \to \tau_{had\text{-}vis}$	40 ± 6
Misidentified jet $\to \tau_{had\text{-}vis}$	196 ± 24
All backgrounds	900 ± 170
H^+ (200 GeV), hMSSM $\tan\beta = 60$	175 ± 28
H^+ (1000 GeV), hMSSM $\tan\beta = 60$	2.0 ± 0.2
Data	890

5. Systematic uncertainties

Several sources of systematic uncertainty, affecting the normalisation of signal and background processes or the shape of their distributions, are considered. The individual sources of systematic uncertainty are assumed to be uncorrelated. However, when applicable, correlations of a given systematic uncertainty are maintained across all processes. All systematic uncertainties are symmetrised with respect to the nominal value.

In order to assess the impact of most detector-related systematic uncertainties, in particular those arising from the simulation of pile-up and object reconstruction, the event selection is re-applied after shifting a particular parameter to its ± 1 standard-deviation value. All instrumental systematic uncertainties arising from the reconstruction, identification and energy scale of electrons, muons, (b-tagged) jets and $\tau_{\text{had-vis}}$ candidates are considered. They are propagated to the reconstructed $E_{\text{T}}^{\text{miss}}$ and an additional uncertainty in its soft term is taken into account. The dominant detector-related systematic uncertainties for this search arise from the reconstruction and identification of $\tau_{\text{had-vis}}$ candidates, from the jet energy scale, from the $\tau_{\text{had-vis}}$ energy scale and from the b-tagging efficiency. Their impacts on the predicted event yield for the dominant background process ($t\bar{t}$) are, respectively, 12%, 11%, 3% and 2%. Systematic uncertainties arising from the reconstruction, identification and energy scale of electrons and muons are found to be negligible. The luminosity uncertainty of 5% is applied directly to the event yields of all simulated events.

The efficiency of the $E_{\text{T}}^{\text{miss}}$ trigger is measured in a control region of the data, as described in Section 4. The parameterisation of the efficiency shows a small dependence on the identification criteria (loose versus nominal) for the electron and the $\tau_{\text{had-vis}}$ candidate, as well as on the minimum number of jets chosen for the control region. This results in small variations of the measured fit function. These variations, as well as the limited statistical precision of the bins used for the fit function and the resulting parameterisation, are accounted for as systematic uncertainties. In the signal region, the total systematic uncertainty arising from the $E_{\text{T}}^{\text{miss}}$ trigger efficiency measurement is about 2%.

In the estimation of backgrounds with jets misidentified as $\tau_{\text{had-vis}}$, the dominant systematic uncertainties arise from the level of contamination of $\tau_{\text{had-vis}}$ objects matching a true τ_{had} decay at generator level and fulfilling the anti-$\tau_{\text{had-vis}}$ selection (varied by 50%), from the statistical limitation due to the control sample size and from the requirement on the BDT score in the anti-$\tau_{\text{had-vis}}$ control sample. When changing the latter, different fractions of gluon- and quark-initiated jets populate the anti-$\tau_{\text{had-vis}}$ control region. The event topology (in particular the shape of the $E_{\text{T}}^{\text{miss}}$ and $\Delta\phi_{\tau,\text{miss}}$ distributions) also depends on the requirement imposed on the BDT score. The corresponding systematic uncertainty is assessed by considering the shape of the m_{T} distribution obtained for two alternative cuts on the BDT score, which are symmetric around the nominal cut value. The impacts of the three systematic uncertainties listed above on the event yield of the background with jets misidentified as $\tau_{\text{had-vis}}$ are, respectively, 8%, 6% and 2%.

The dominant background process with a true τ_{had} is the production of $t\bar{t}$ pairs and single-top-quark events, for which an overall cross-section uncertainty of 6% is applied, incorporating scale, PDF+α_{s} and top-quark mass uncertainties [47,80,81]. In addition, systematic uncertainties due to the choice of parton shower and hadronisation models are derived by comparing $t\bar{t}$ events generated with POWHEG-BOX interfaced to either PYTHIA v8.210 or HERWIG++ v2.7.1 [82], which uses the UEEE5 [83] underlying-event tune. The systematic uncertainties arising from initial- and final-state parton radiation, which modify the jet production rate, are computed with the same packages as for the baseline $t\bar{t}$ event generation, by setting the corresponding parameters in PYTHIA to a range of values not excluded by the experimental data. Finally, the uncertainty due to the choice of matrix-element generator is evaluated by comparing samples generated with MADGRAPH5_AMC@NLO or POWHEG-BOX, both using the CTEQ6L1 PDF set and interfaced to HERWIG++. The impacts of the three systematic uncertainties listed above on the event yield of the $t\bar{t}$ background are, respectively, 16%, 7% and 15%.

For the sub-leading background process with a true τ_{had}, $W \to \tau\nu$, a systematic uncertainty of 3% is assigned to the overall renormalisation factor, as obtained by changing various selection criteria for the control region enriched with such background events. For Z+jets and diboson production, theoretical uncertainties of 5% and 6% are considered, respectively, combining PDF+α_{s} and scale variation uncertainties in quadrature.

Systematic uncertainties in the H^+ signal generation are estimated as follows. The uncertainty arising from the QCD scale is obtained by varying the factorisation and renormalisation scale up and down by a factor of two. The largest variation of the signal acceptance is then symmetrised and taken as the scale uncertainty, 4–8% depending on the H^+ mass hypothesis. The variation of the signal acceptance with various PDF sets is estimated using LHAPDF [84], but is found to be negligible for all signal samples. Finally, the impact of A14 tune variations on the signal acceptance is estimated by adding in quadrature the positive and negative excursions from a subset of tune variations that cover underlying-event and jet-structure effects, as well as different aspects of extra jet production. This uncertainty amounts to 8–10% and is of the same order as the sum in quadrature of the detector-related systematic uncertainties for the H^+ signal samples.

6. Results

In order to test the compatibility of the data with the background-only and signal + background hypotheses, a profile likelihood ratio [85] is used, with m_{T} as the discriminating variable. The statistical analysis is based on a binned likelihood function for this distribution. All systematic uncertainties from theoretical or experimental sources are implemented as nuisance parameters. The parameter of interest (or signal strength) $\mu \equiv \sigma(pp \to [b]tH^{\pm}) \times \text{BR}(H^{\pm} \to \tau\nu)$, and the nuisance parameters are simultaneously fitted by means of a negative log-likelihood minimisation. Expected limits are derived using the asymptotic approximation of the distribution of the test statistic [86].

Fig. 5 shows the m_{T} distribution obtained after a fit with the background-only hypothesis, together with the m_{T} distributions corresponding to two H^+ mass hypotheses: 200 and 1000 GeV. The binning shown in Fig. 5 is also used in the statistical analysis. The SM predictions are found to be consistent with the data, and exclusion limits are set on $\sigma(pp \to [b]tH^{\pm}) \times \text{BR}(H^{\pm} \to \tau\nu)$ by rejecting the signal hypothesis at the 95% confidence level (CL) using the CL$_s$ procedure [87]. Fig. 6 shows the observed and expected exclusion limits. They agree within the uncertainties over the explored H^+ mass range. The observed limits range from 1.9 pb to 15 fb in the mass range 200–2000 GeV. For the largest charged Higgs boson mass hypotheses, the exclusion limits show very little dependence on m_{H^+}, as there is only one bin entering the fit for $m_{\text{T}} > 500$ GeV. The impact from the various sources of systematic uncertainty on the expected 95% CL exclusion limits are summarised in Table 2, for H^+ mass hypotheses of 200 and 1000 GeV. The impact of the systematic uncertainties reported in Section 5 only represents the relative change in event yields. In the limit-setting procedure, however, m_{T} shape variations are also taken into account, leading to a different relative importance of the various systematic uncertainties. Those with a large impact over the ex-

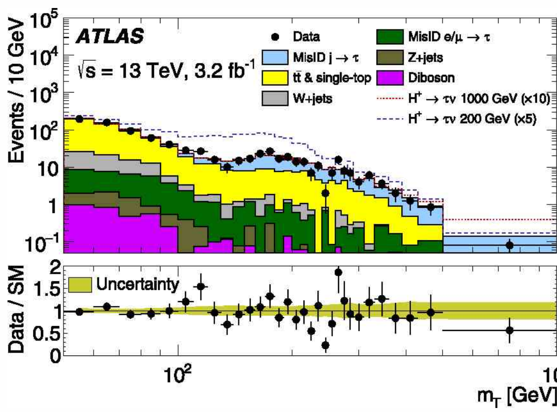

Fig. 5. Distribution of m_T after full event selection and a fit to the data with the background-only hypothesis. The horizontal axis starts at $m_T = 50$ GeV and is in logarithmic scale. Two H^+ signal hypotheses are included separately on the stack. The signal sample at 200 (1000) GeV is scaled to 5 (10) times the cross section predicted at $\tan\beta = 60$ in the hMSSM benchmark scenario. Bins are 10 GeV in width up to 310 GeV and then have a varying size. The last bin includes all overflow events. The total (statistical and systematic) uncertainties in the SM prediction are shown in the lower plot.

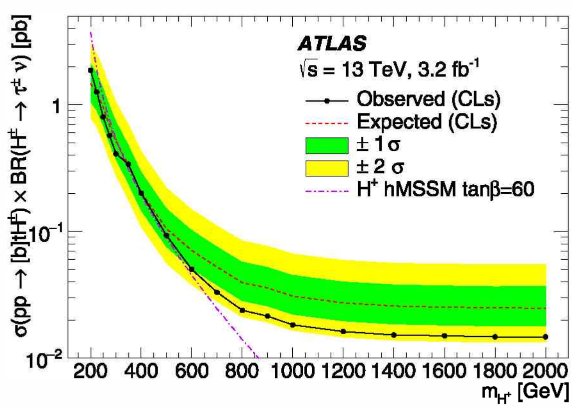

Fig. 6. Observed and expected 95% CL exclusion limits for heavy charged Higgs boson production as a function of m_{H^+} in 3.2 fb^{-1} of pp collision data. The prediction for $\sigma(pp \to [b]tH^{\pm}) \times \mathrm{BR}(H^{\pm} \to \tau\nu)$ as a function of the charged Higgs boson mass is also shown as a dotted-dashed line, for $\tan\beta = 60$ in the hMSSM benchmark scenario.

plored mass range are the $\tau_{\text{had-vis}}$ identification and energy-scale uncertainties, the $t\bar{t}$ background modelling uncertainties, and the statistical precision in the estimation of the background with a jet misidentified as a $\tau_{\text{had-vis}}$. For the larger H^+ mass hypotheses, the signal modelling uncertainties also have a significant impact. The total uncertainty is dominated by the statistical uncertainty.

The limits in Fig. 6 are presented together with an illustrative signal prediction in the hMSSM benchmark scenario. Fig. 7 shows the 95% CL exclusion limits on $\tan\beta$ as a function of m_{H^+} in the context of the hMSSM, compared with the Run 1 results. Values of $\tan\beta$ in the range 42–60 are excluded for a charged Higgs boson mass of 200 GeV. At $\tan\beta = 60$, above which no reliable theoretical calculations exist, the H^+ mass range from 200 to 340 GeV is excluded. The limits of this search surpass those obtained with the pp collision data at $\sqrt{s} = 8$ TeV [11].

7. Conclusion

A search for charged Higgs bosons produced in association with a single top quark and subsequently decaying via $H^+ \to \tau\nu$ is performed, based on fully hadronic final states. The dataset used for this analysis contains 3.2 fb^{-1} of pp collisions at $\sqrt{s} =$ 13 TeV, recorded in 2015 by the ATLAS detector at the LHC. The background-only hypothesis is found to be in agreement with the data. Upper limits are set on the production cross section times branching fraction between 1.9 pb and 15 fb for a charged Higgs boson mass range of 200–2000 GeV. In the context of the hMSSM, values of $\tan\beta$ in the range 42–60 are excluded for a charged Higgs boson mass of 200 GeV. At $\tan\beta = 60$, above which no reliable theoretical calculations exist, the H^+ mass range from 200 to 340 GeV is excluded.

Table 2
Impact of various sources of uncertainty on the expected 95% CL exclusion limit, for two H^+ mass hypotheses: 200 and 1000 GeV. The impact is obtained by comparing the nominal expected limit with the expected limit when a certain set of uncertainties is not included in the limit-setting procedure.

Source of systematic uncertainty	Impact on the expected limit (in %)	
	$m_{H^+} = 200$ GeV	$m_{H^+} = 1000$ GeV
Experimental		
luminosity	2.0	1.1
trigger	< 0.1	< 0.1
$\tau_{\text{had-vis}}$	2.7	1.1
jet	0.4	< 0.1
E_T^{miss}	0.3	< 0.1
Fake factors		
statistical limitation	4.5	0.7
true τ_{had} contamination	< 0.1	< 0.1
anti-$\tau_{\text{had-vis}}$ BDT score	0.2	0.6
Signal and background models		
$t\bar{t}$ cross section	0.2	< 0.1
$t\bar{t}$ modelling	7.5	1.0
H^+ signal modelling	1.4	1.3

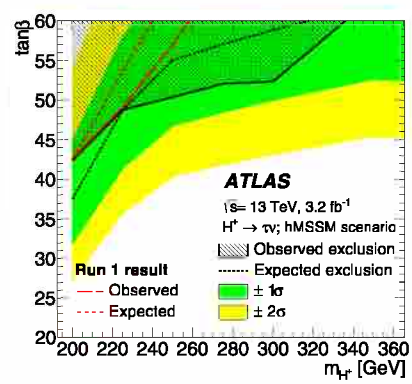

Fig. 7. 95% CL exclusion limits on $\tan\beta$ as a function of m_{H^+}, shown in the context of the hMSSM, for the regions in which reliable theoretical calculations exist ($\tan\beta \leq 60$). As a comparison, the two lighter dashed curves (in red in the web version of this article) in the upper-left corner show the observed and expected exclusion limits from Run 1 analyses of pp collisions measured at $\sqrt{s} = 8$ TeV by ATLAS [11].

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