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Search for charged Higgs bosons decaying via $H^{\pm} \to \tau^{\pm}\nu$ in fully hadronic final states using pp collision data at $\sqrt{s} = 8$ TeV with the ATLAS detector

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Abstract: The results of a search for charged Higgs bosons decaying to a τ lepton and a neutrino, $H^{\pm} \to \tau^{\pm}\nu$, are presented. The analysis is based on $19.5\,\mathrm{fb}^{-1}$ of proton-proton collision data at $\sqrt{s} = 8$ TeV collected by the ATLAS experiment at the Large Hadron Collider. Charged Higgs bosons are searched for in events consistent with top-quark pair production or in associated production with a top quark, depending on the considered $H^{\pm}$ mass. The final state is characterised by the presence of a hadronic τ decay, missing transverse momentum, b-tagged jets, a hadronically decaying W boson, and the absence of any isolated electrons or muons with high transverse momenta. The data are consistent with the expected background from Standard Model processes. A statistical analysis leads to 95% confidence-level upper limits on the product of branching ratios $\mathcal{B}(t \to bH^{\pm}) \times \mathcal{B}(H^{\pm} \to \tau^{\pm}\nu)$, between 0.23% and 1.3% for charged Higgs boson masses in the range 80–160 GeV. It also leads to 95% confidence-level upper limits on the production cross section times branching ratio, $\sigma(pp \to tH^{\pm} + X) \times \mathcal{B}(H^{\pm} \to \tau^{\pm}\nu)$, between 0.76 pb and 4.5 fb, for charged Higgs boson masses ranging from 180 GeV to 1000 GeV. In the context of different scenarios of the Minimal Supersymmetric Standard Model, these results exclude nearly all values of $\tan\beta$ above one for charged Higgs boson masses between 80 GeV and 160 GeV, and exclude a region of parameter space with high $\tan\beta$ for $H^{\pm}$ masses between 200 GeV and 250 GeV.

Keywords: Supersymmetry, Hadron-Hadron Scattering, Beyond Standard Model, Higgs physics

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1 Introduction

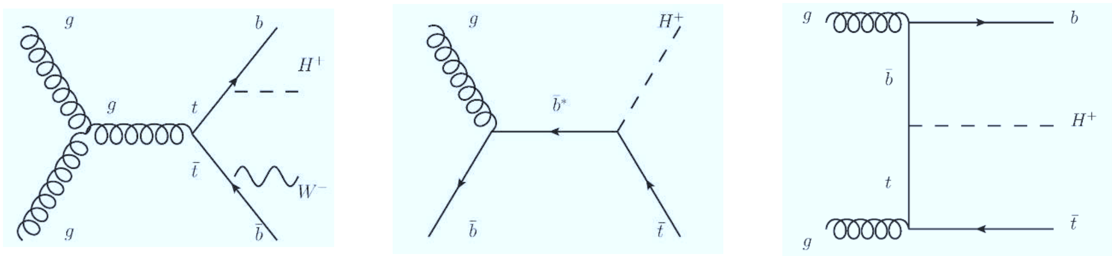
Charged Higgs bosons (H^+, H^-) are predicted by several non-minimal Higgs scenarios, such as two-Higgs-doublet Models (2HDM) [1] or models containing Higgs triplets [2–6]. As the Standard Model (SM) does not contain any elementary charged scalar particle, the observation of a charged Higgs boson[1] would clearly indicate new phenomena beyond the SM. For instance, supersymmetric models predict the existence of charged Higgs bosons. In a type-II 2HDM, such as the Higgs sector of the Minimal Supersymmetric Standard Model (MSSM) [7–11], the main H^+ production mode at the Large Hadron Collider (LHC) would

[1]In the following, charged Higgs bosons are denoted by H^+, and the charge-conjugate is implied.

be through top-quark decays $t \to bH^+$, for charged Higgs boson masses (m_{H^+}) smaller than the top-quark mass ($m_{\rm top}$). At the LHC, top quarks are produced predominantly through $t\bar{t}$ production. In this paper, the contribution to $t \to bH^+$ which may arise from single top-quark production is neglected, since the signal production cross section through this channel is very small with respect to $t\bar{t}$ production. A diagram illustrating the leading-order production mechanism is shown on the left-hand side of figure 1. For charged Higgs boson masses larger than $m_{\rm top}$, the main H^+ source at the LHC is through associated production with a top quark. An additional b-quark can also appear in the final state. The leading-order production mechanisms in two different approximations are illustrated in the centre and right-hand side diagrams of figure 1: in the four-flavour scheme (4FS) b-quarks are dynamically produced, whereas in the five-flavour scheme (5FS) the b-quark is also considered as an active flavour inside the proton. Their cross sections are matched according to ref. [12], and an evaluation of the two schemes can be found in ref. [13].

In the MSSM, the Higgs sector can be completely determined at tree level by one of the Higgs boson masses, here taken to be m_{H^+}, and $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets. For $m_{H^+} < m_{\rm top}$, the decay via $H^+ \to \tau^+\nu$ is dominant for $\tan\beta > 2$ and remains sizeable for $1 < \tan\beta < 2$. For higher m_{H^+}, the decay via $H^+ \to \tau^+\nu$ is still significant, especially for large values of $\tan\beta$ [14]. The combined LEP lower limit for the charged Higgs boson mass is about 90 GeV [15]. The Tevatron experiments placed upper limits on $\mathcal{B}(t \to bH^+)$ in the 15–20% range for $m_{\rm H^+} < m_{\rm top}$ [16, 17]. In a previous search based on data taken at $\sqrt{s} = 7$ TeV with the ATLAS and CMS detectors, the limits on $\mathcal{B}(t \to bH^+)$ were lowered to the range 0.8–4% [18, 19]. For all of these results, $\mathcal{B}(H^+ \to \tau^+\nu) = 100\%$ was assumed.

This paper describes a search for charged Higgs bosons with masses in the ranges 80–160 GeV and 180–1000 GeV. The region 160 GeV $< m_{H^+} <$ 180 GeV is not considered in this paper, since there is currently no reliable theoretical treatment for the interference between the different H^+ production modes in this transition region [20]. The final state studied is characterised by the presence of a hadronic τ decay ($\tau_{\rm had}$), missing transverse momentum ($E_{\rm T}^{\rm miss}$), b-quark-initiated jets, a hadronically decaying W boson, and the absence of any isolated electrons or muons with high transverse momenta. In addition to the large branching ratio for a τ to decay hadronically, this final state contains only neutrinos associated with the H^+ production and decay, resulting in good discriminating power between SM and signal processes. Charged Higgs bosons are searched for in a model-independent way, hence results are given in terms of $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to \tau^+\nu)$ (low-mass search, $m_{H^+} < m_{\rm top}$) and $\sigma(pp \to \bar{t}H^+ + X) \times \mathcal{B}(H^+ \to \tau^+\nu)$ (high-mass search, $m_{H^+} > m_{\rm top}$). These limits are then also interpreted in different MSSM scenarios. The results are based on 19.5 fb^{-1} of data from pp collisions at $\sqrt{s} = 8$ TeV, collected in 2012 with the ATLAS detector at the LHC. The final state analysed for the low-mass search is $t\bar{t} \to b\bar{b}W^-H^+ \to b\bar{b}(q\bar{q}')(\tau^+_{\rm had}\nu)$. The final state is similar or identical for the high-mass search, depending on whether the additional b-quark-initiated jet is seen in the detector, $gb \to \bar{t}H^+ \to (W^-\bar{b})H^+ \to (q\bar{q}'\bar{b})(\tau^+_{\rm had}\nu)$ in the 5FS case and $gg \to \bar{t}bH^+ \to (W^-\bar{b})bH^+ \to (q\bar{q}'\bar{b})b(\tau^+_{\rm had}\nu)$ in the 4FS case.



(a) Low-mass H^+ production. **(b)** 5FS high-mass H^+ production. **(c)** 4FS high-mass H^+ production.

Figure 1. Leading-order Feynman diagrams for the dominant production modes of charged Higgs bosons at masses (a) below and (b, c) above the top-quark mass.

This paper is organised as follows. In section 2, the data and simulated samples used in this analysis are described. In section 3, the reconstruction of physics objects in ATLAS is discussed. The event selection and background modelling are presented in section 4. Systematic uncertainties are discussed in section 5, and the limit-setting procedure is described in section 6. Exclusion limits in terms of $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to \tau^+\nu)$ (low-mass) and $\sigma(pp \to \bar{t}H^+ + X) \times \mathcal{B}(H^+ \to \tau^+\nu)$ (high-mass) as well as model-dependent exclusion contours are presented in section 7.

2 Data and simulated events

The ATLAS detector [21] consists of an inner tracking 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 tracks in the field of three superconducting toroid magnets. A three-level trigger system is used. The first-level trigger (L1) is implemented in hardware, using a subset of detector information to reduce the event rate to no more than 75 kHz. This is followed by two software-based trigger levels (L2 and EF), which together further reduce the event rate to less than 1 kHz.

Only data taken with all ATLAS subsystems operational are used. Stringent detector and data quality requirements are applied, resulting in an integrated luminosity of 19.5 fb^{-1} for the 2012 data-taking period. The integrated luminosity has an uncertainty of 2.8%, measured following the methodology described in ref. [22]. Events are required to have a primary vertex with at least five associated tracks, each with a transverse momentum p_{T} greater than 400 MeV. The primary vertex is defined as the reconstructed vertex with the largest sum of squared track transverse momenta.

[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 upwards. 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 $\eta = -\ln\tan(\theta/2)$.

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The background processes to this search include SM pair production of top quarks, as well as the production of single top-quark, W+jets, Z/γ^*+jets, diboson and multi-jet events. These backgrounds are categorised based on the type of reconstructed objects identified as the visible decay products[3] of the hadronically decaying τ candidate ($\tau_{\text{had-vis}}$). The dominant backgrounds in this analysis, those containing a true τ_{had}, where the $\tau_{\text{had-vis}}$ is correctly identified, or a jet misidentified as a $\tau_{\text{had-vis}}$ candidate, are estimated in a data-driven way (sections 4.2 and 4.3), while simulation samples are used to estimate the minor background arising from events with a lepton misidentified as a $\tau_{\text{had-vis}}$ (1–2% of the total background). Simulation samples are also used to develop and validate the analysis.

The modelling of SM $t\bar{t}$ and single top-quark events is performed with MC@NLO [23, 24], except for t-channel single top-quark production, for which AcerMC [25] is used. The top-quark mass is set to 172.5 GeV and the set of parton distribution functions used is CT10 [26]. For events generated with MC@NLO, the parton shower, hadronisation and underlying event are added using HERWIG [27] and JIMMY [28]. PYTHIA6 [29] is used instead for events generated with AcerMC. Inclusive cross sections are taken from the approximate next-to-next-to-leading-order (NNLO) predictions for $t\bar{t}$ production [30], for single top-quark production in the t-channel and s-channel [31, 32], as well as for Wt production [33]. Overlaps between SM Wt and $t\bar{t}$ final states are removed [24]. Single vector boson (W and Z/γ^*) production is simulated with up to five accompanying partons, using ALPGEN [34] interfaced to HERWIG and JIMMY, and using the CTEQ6L1 [35] parton distribution functions. The additional partons produced in the matrix-element part of the event generation can be light partons or heavy quarks. In the latter case, ALPGEN is also used to generate dedicated samples with matrix elements for the production of massive $b\bar{b}$ or $c\bar{c}$ pairs. Diboson events (WW, WZ and ZZ) are generated using HERWIG. The cross sections are normalised to NNLO predictions for W-boson and Z/γ^* production [36, 37] and to next-to-leading-order (NLO) predictions for diboson production [38]. The SM background samples are summarised in table 1.

Signal samples are produced with PYTHIA 6 for 80 GeV $\leq m_{H^+} \leq$ 160 GeV in m_{H^+} intervals of 10 GeV separately for $t\bar{t} \to b\bar{b}H^+W^-$ and $t\bar{t} \to b\bar{b}H^-W^+$, where the charged Higgs bosons decay via $H^+ \to \tau^+\nu$. The process $t\bar{t} \to b\bar{b}H^+H^-$ gives a very small contribution to the signal region, which is negligible after the event selection described in section 4.1. The cross section for these processes depends only on the total $t\bar{t}$ production cross section and the branching ratio $\mathcal{B}(t \to bH^+)$. For 180 GeV $\leq m_{H^+} \leq$ 1000 GeV, the simulation of the signal for top-quark associated H^+ production is performed with POWHEG [39] interfaced to PYTHIA 8 [40]. For 180 GeV $\leq m_{H^+} \leq$ 200 GeV, samples are produced in m_{H^+} steps of 10 GeV, then in intervals of 25 GeV up to m_{H^+} = 300 GeV and in intervals of 50 GeV for $m_{H^+} \leq$ 600 GeV. Additionally, signal mass points at m_{H^+} = 750 GeV and m_{H^+} = 1000 GeV are produced. The production cross section for the high-mass charged Higgs boson is computed using the 4FS and 5FS, including theoretical uncertainties, and combined according to ref. [12]. The samples are generated at NLO using the 5FS and the narrow-width approximation for the H^+. Possible effects from the interference between

[3] This refers to the non-neutrino decay products.

Process	Generator	Cross section [pb]	
SM $t\bar{t}$ (inclusive)	MC@NLO	253	[30]
Single top-quark t-channel (≥ 1 lepton)	AcerMC	28.4	[31]
Single top-quark s-channel (≥ 1 lepton)	MC@NLO	1.8	[32]
Single top-quark Wt-channel (inclusive)	MC@NLO	22.4	[33]
$W \to \ell\nu$	ALPGEN	3.6×10^4	[36]
$Z/\gamma^* \to \ell\ell$ with $m(\ell\ell) > 10$ GeV	ALPGEN	1.7×10^4	[37]
WW (≥ 1 electron/muon)	HERWIG	20.9	[38]
ZZ (≥ 1 electron/muon)	HERWIG	1.5	[38]
WZ (≥ 1 electron/muon)	HERWIG	7.0	[38]
H^+ signal ($m_{H^+} = 250\,\text{GeV}$)	POWHEG	0.5	

Table 1. Cross sections for the simulated processes and reference generators used to model them. For the high-mass H^+ signal selection, the value shown is the cross section times $\mathcal{B}(H^+ \to \tau^+\nu)$ for the MSSM m_h^{max} scenario [41, 42], corresponding to $m_{H^+} = 250\,\text{GeV}$ and $\tan\beta = 50$. This cross section includes both H^+ and H^- production. The low-mass signal, which is not included in the table, assumes one H^+ produced per $t\bar{t}$ decay, so it is a fraction of the $t\bar{t}$ cross section. The previously published upper limit on $\mathcal{B}(t \to bH^+)$ for $m_{H^+} = 130\,\text{GeV}$ is 0.9% [18].

the production of a charged Higgs boson through $t\bar{t}$ and top-quark associated production are not taken into account.

The event generators are tuned to describe the ATLAS data. In samples where PYTHIA 6 is interfaced to AcerMC, the AUET2B [43] tune is used. The Perugia 2011 C tune [44] is used when PYTHIA 6 is interfaced to POWHEG. For the samples generated with HERWIG, the AUET2 [45] tune is used. In all samples with τ leptons, except for those simulated with PYTHIA 8,[4] TAUOLA [46] is used for the τ decays. PHOTOS [47] is used for photon radiation from charged leptons in all samples where applicable.

To take into account the presence of multiple proton-proton interactions occurring in the same and neighbouring bunch crossings (referred to as pile-up), simulated minimum-bias events are added to the hard process in each generated event. Prior to the analysis, simulated events are reweighted in order to match the distribution of the average number of pile-up interactions in the data. All generated events are propagated through a detailed GEANT4 simulation [48, 49] of the ATLAS detector and are reconstructed with the same algorithms as the data.

3 Physics object selection

Jets are reconstructed from energy deposits in the calorimeters, using the anti-k_t algorithm [50, 51] with a radius parameter of $R = 0.4$. Jets are required to have $p_{\mathrm{T}} > 25\,\text{GeV}$

[4] So-called "sophisticated tau-decays" have been available in PYTHIA since version 8.150 such that the usage of TAUOLA is not necessary.

and $|\eta| < 2.5$. To reduce the contribution of jets initiated by pile-up, jets with $p_{\mathrm{T}} < 50$ GeV and $|\eta| < 2.4$ must pass the requirement that at least half of the p_{T} of the tracks associated with the jet is contributed by tracks matched to the primary vertex [52]. An algorithm identifies jets containing b-quarks by combining impact parameter information with the explicit determination of a secondary vertex [53], and these are referred to as b-tagged jets. A working point corresponding to a 70% efficiency for identifying b-quark-initiated jets is used.

Candidates for identification as $\tau_{\text{had-vis}}$ arise from jets reconstructed from energy deposits in calorimeters, again using the anti-k_t algorithm with a radius parameter of $R = 0.4$, which have $p_{\mathrm{T}} > 10$ GeV and one or three charged-particle tracks within a cone of size of $\Delta R < 0.2$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ around the $\tau_{\text{had-vis}}$ axis [54]. These candidates are further required to have a visible transverse momentum (p_{T}^{τ}) of at least 20 GeV and to be within $|\eta| < 2.3$. The output of boosted decision tree algorithms [55, 56] is used to distinguish $\tau_{\text{had-vis}}$ from jets not initiated by τ leptons, separately for τ_{had} decays with one or three charged-particle tracks. In this analysis, a point with 40% (35%) efficiency for identification of 1(3)-prong $\tau_{\text{had-vis}}$ is used, and this requirement is referred to as the $\tau_{\text{had-vis}}$ identification. Dedicated algorithms are used to reject electrons and muons that are incorrectly identified as $\tau_{\text{had-vis}}$ [54]. After these algorithms are applied, the backgrounds arising from muons and electrons misidentified as $\tau_{\text{had-vis}}$ are very small, although there is still a sizeable background from jets misidentified as $\tau_{\text{had-vis}}$.

The $E_{\mathrm{T}}^{\mathrm{miss}}$ is defined as the magnitude of the negative vectorial sum of transverse momenta of muons and energy deposits in the calorimeter. It is computed using fully calibrated and reconstructed physics objects [57].

The final states considered in this search contain no charged leptons, hence events containing isolated electron or muon candidates with high transverse momenta are rejected. Electron candidates are reconstructed from energy deposits in the calorimeter that are matched to tracks in the inner detector, taking losses due to bremsstrahlung into account. They are required to have a transverse energy (E_{T}) greater than 25 GeV and to be within $|\eta| < 2.47$ (the transition region between the barrel and end-cap calorimeters, $1.37 < |\eta| < 1.52$, is excluded) [58, 59]. Muon candidates must pass tracking requirements in both the inner detector and the muon spectrometer, have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$ [60]. Additionally, electron candidates are required to pass pile-up-corrected 90% efficient calorimeter- and track-based isolation, with ΔR cone sizes of 0.2 and 0.3, respectively, while muon candidates are required to pass a relative track-based isolation of < 0.05 with a ΔR cone < 0.4 [61].

4 Event selection and background modelling

4.1 Event selection

The analysis uses events passing a $\tau_{\text{had-vis}}$+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger. The $\tau_{\text{had-vis}}$ trigger is defined by calorimeter energy in a narrow core region and an isolation region at L1, a basic combination of tracking and calorimeter information at L2 and more sophisticated algorithms imported from the offline reconstruction at the EF. The $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger uses calorimeter information at all levels with a more refined algorithm at the EF. The EF threshold on the transverse momentum of the $\tau_{\text{had-vis}}$ trigger object is 27 GeV or 29 GeV, and for the $E_{\text{T}}^{\text{miss}}$ trigger the EF threshold is 40 GeV or 50 GeV. The multiple trigger thresholds are the result of slight changes of the trigger definition during the 2012 data-taking period, for which 50% of events had EF thresholds at 27 GeV and 50 GeV, 43% at 29 GeV and 50 GeV, and 7% at 29 GeV and 40 GeV, for the $\tau_{\text{had-vis}}$ and $E_{\text{T}}^{\text{miss}}$ triggers, respectively.

Further event filtering is performed by discarding events in which any jet with $p_{\text{T}} >$ 25 GeV fails the quality cuts discussed in ref. [62]. This ensures that no jet is consistent with having originated from instrumental effects or non-collision backgrounds. The following requirements are then applied:

- at least four (three) selected jets for the low-mass (high-mass) signal selection;
- at least one of these selected jets being b-tagged at the 70%-efficient working point;
- exactly one selected $\tau_{\text{had-vis}}$ with $p_{\text{T}}^{\tau} > 40$ GeV matched to a $\tau_{\text{had-vis}}$ trigger object (trigger-matched);
- no selected electron or muon in the event;
- $E_{\text{T}}^{\text{miss}} > 65$ (80) GeV for the low-mass (high-mass) signal selection;
- $E_{\text{T}}^{\text{miss}}/\sqrt{\sum p_{\text{T}}^{\text{PV trk}}} > 6.5$ (6.0) GeV$^{1/2}$ for the low-mass (high-mass) signal selection, where $\sum p_{\text{T}}^{\text{PV trk}}$ is the sum of transverse momenta of all tracks originating from the primary vertex. This is to reject events in which a large reconstructed $E_{\text{T}}^{\text{miss}}$ is due to the limited resolution of the energy measurement.

For the selected events, the transverse mass (m_{T}) of the $\tau_{\text{had-vis}}$ and $E_{\text{T}}^{\text{miss}}$ is defined as:

$$m_{\text{T}} = \sqrt{2 p_{\text{T}}^{\tau} E_{\text{T}}^{\text{miss}} (1 - \cos \Delta\phi_{\tau,\text{miss}})}, \tag{4.1}$$

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 $W \to \tau\nu$ background events and less than the H^+ mass for signal events, in the absence of detector resolution effects.

A minimal requirement is placed on m_{T} at 20 (40) GeV in the low-mass (high-mass) H^+ search. This requirement is motivated in section 4.2. After the full event selection, the signal has an acceptance of 0.30–0.60% for the low-mass range, and 1.7–5.8% for the high-mass range, where in both cases the acceptance increases with increasing m_{H^+}. The acceptances are evaluated with respect to signal samples where both the τ lepton and the associated top quark decay inclusively.

4.2 Data-driven estimation of the backgrounds with a true τ_{had}

An embedding method [63] is used to estimate the backgrounds that contain a real τ_{had} from a vector boson decay. The method is based on a control data sample of μ+jets events satisfying criteria similar to those of the signal selection except for the $\tau_{\text{had-vis}}$ requirements and replacing the detector signature of the muon by a simulated hadronic τ decay. The method is applied to a control region of μ+jets events, rather than e+jets, due to the clean signature and the relative ease with which the measured muon can be removed. These new hybrid events are then used for the background prediction. An advantage of this approach, compared to simulation, is that with the exception of the τ_{had}, the estimate is extracted from data; this includes the contributions from the underlying event and pile-up, jets, and all sources of $E_{\text{T}}^{\text{miss}}$ except for the neutrino from the τ_{had} decay. Furthermore, since the normalisation of the background estimate is evaluated from the data, assuming lepton universality of the W boson decay, the method does not rely on theoretical cross sections and their uncertainties. This embedding method has been used in previous charged Higgs boson searches [64] as well as in SM $H \to \tau\tau$ [65, 66] analyses.

To select the μ+jets sample from the data, the following requirements are made:

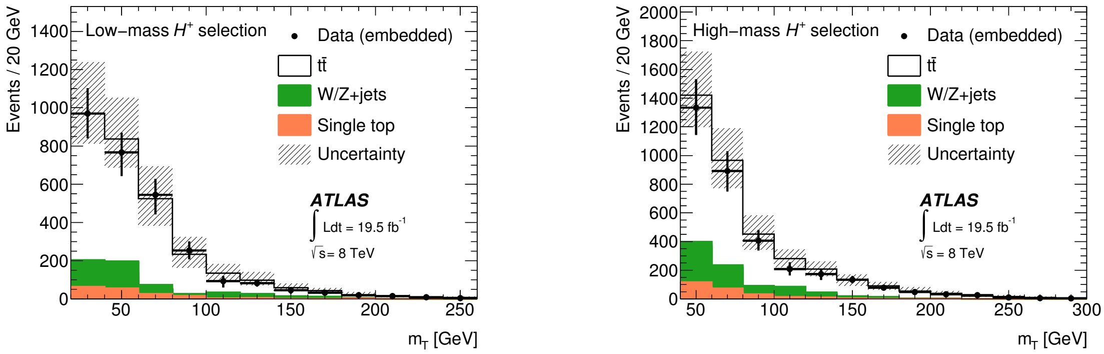
- a single-muon trigger with a p_{T} threshold of 24 GeV or 36 GeV (single-muon triggers with two different p_{T} thresholds are used, since the lower-threshold trigger also requires the muon to be isolated);
- exactly one isolated muon with $p_{\text{T}} > 25$ GeV and no isolated electron with $E_{\text{T}} > 25$ GeV;
- at least four (three) jets with $p_{\text{T}} > 25$ GeV for the low-mass (high-mass) charged Higgs boson search, at least one of which is b-tagged;
- $E_{\text{T}}^{\text{miss}} > 25$ (40) GeV for the low-mass (high-mass) charged Higgs boson search.

This selection is looser than the selection defined in section 4.1 in order not to bias the sample. However, the $E_{\text{T}}^{\text{miss}}$ cut in the μ+jets sample selection removes events with very low m_{T}. Thus, a cut on $m_{\text{T}} > 20$ (40) GeV is introduced in the search for low-mass (high-mass) charged Higgs bosons to remove this bias. With this selection, there is a possible small contamination from signal events with a leptonically decaying τ lepton. This small contamination, which is estimated using simulation, has a much softer m_{T} distribution than the signal with τ_{had}, and is observed to have a negligible impact on the evaluation of signal strength or exclusion limits. Contamination from leptonically decaying τ leptons from W decays is accounted for in the overall normalisation ($c_{\tau\to\mu}$ in eq. (4.3)).

To replace a muon in the selected data, the track that is associated with the muon is removed. The energy deposited in the calorimeters is removed by simulating a $W \to \mu\nu$ event with the same kinematics as in the selected data event and identifying the corresponding cells. Thus, the removal of energy deposits not associated with the selected muon is minimised. The momentum of the muon in selected events is extracted and rescaled to account for the higher τ lepton mass,

$$\vec{p}_\tau = \frac{\sqrt{E_\mu^2 - m_\tau^2}}{\sqrt{\vec{p}_\mu \cdot \vec{p}_\mu}} \vec{p}_\mu, \tag{4.2}$$

where $\vec{p}_\tau$ is the rescaled momentum, E_μ is the reconstructed energy of the muon, m_τ is the τ mass, and $\vec{p}_\mu$ is the reconstructed muon momentum. The τ lepton with rescaled momentum



(a) Low-mass H^+ selection. **(b)** High-mass H^+ selection.

Figure 2. Comparison of the m_{T} distributions for events with a true τ_{had} for the (a) low-mass and (b) high-mass charged Higgs boson search, as predicted by the embedding method and simulation. Combined statistical and systematic uncertainties (as described in section 5) for the embedded sample are shown as error bars, and all systematic uncertainties applicable to simulation are shown as hatched bands.

is further processed by TAUOLA to produce the hadronic τ decay and account for the τ polarisation as well as for final-state radiation. The τ lepton decay products are propagated through the full detector simulation and reconstruction. Events referred to as containing a true τ_{had} are those with a genuine τ_{had} as expected from the embedding method.

The shape of the m_{T} distributions for backgrounds with a true τ_{had} is taken from the distribution obtained with the embedded events, after applying the corresponding signal selection. The normalisation is then derived from the number of embedded events:

$$N_\tau = N_{\mathrm{embedded}} \cdot (1 - c_{\tau\to\mu}) \frac{\epsilon^{\tau+E_{\mathrm{T}}^{\mathrm{miss}}-\mathrm{trigger}}}{\epsilon^{\mu-\mathrm{ID,trigger}}} \times \mathcal{B}(\tau \to \mathrm{hadrons} + \nu), \tag{4.3}$$

where N_τ is the estimated number of events with a true τ_{had}, N_{embedded} is the number of embedded events in the signal region, $c_{\tau\to\mu}$ is the fraction of events in which the selected muon is a decay product of a τ lepton (taken from simulation, about 4%), $\epsilon^{\tau+E_{\mathrm{T}}^{\mathrm{miss}}-\mathrm{trigger}}$ is the $\tau_{\text{had-vis}}+E_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiency (as a function of p_{T}^{τ} and $E_{\mathrm{T}}^{\mathrm{miss}}$, derived from data, see section 4.5), $\epsilon^{\mu-\mathrm{ID,trigger}}$ is the muon trigger and identification efficiency (as a function of p_T and η, derived from data) and $\mathcal{B}(\tau \to \mathrm{hadrons} + \nu)$ is the branching ratio of the τ lepton decays to hadrons.

The m_{T} distributions for selected events with a true τ_{had}, as obtained with the embedding method, are shown in figure 2 and compared to simulation. Embedded data and simulation agree well and are within uncertainties. The combined systematic and statistical uncertainties on the embedded prediction and simulation are compared directly in figure 2, where the reduction provided by the use of the embedding method is shown.

4.3 Data-driven estimation of the multi-jet backgrounds

For the data-driven estimation of the backgrounds with a jet misidentified as a $\tau_{\text{had-vis}}$ (multi-jet background), two data samples are defined, differing only in $\tau_{\text{had-vis}}$ identification

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criteria. The *tight* sample contains a larger fraction of events with a real $\tau_{\text{had-vis}}$, which are required to pass the *tight* $\tau_{\text{had-vis}}$ identification selection described in the object selection, in addition to the trigger matching required in the event selection of section 4.1. The *loose* sample, which contains a larger fraction of events with a misidentified $\tau_{\text{had-vis}}$, is obtained by removing the $\tau_{\text{had-vis}}$ identification requirement that was applied in the *tight* sample. By construction, the *tight* data sample is a subset of the *loose* data sample.

The *loose* sample consists of N_{r} and N_{m} events with, respectively, a real or misidentified $\tau_{\text{had-vis}}$. It is also composed of N_{L} events with a $\tau_{\text{had-vis}}$ passing a *loose but not tight* selection, and N_{T} events in which the $\tau_{\text{had-vis}}$ fulfils the *tight* selection. Using the efficiencies p_{r} and p_{m}, respectively, for a real or misidentified *loose* $\tau_{\text{had-vis}}$ satisfying the *tight* criteria, the following relation can be established:

$$\begin{pmatrix} N_{\text{T}} \\ N_{\text{L}} \end{pmatrix} = \begin{pmatrix} p_{\text{r}} & p_{\text{m}} \\ (1-p_{\text{r}}) & (1-p_{\text{m}}) \end{pmatrix} \times \begin{pmatrix} N_{\text{r}} \\ N_{\text{m}} \end{pmatrix}. \tag{4.4}$$

In turn, inverting the 2×2 matrix above, the number of events in which the misidentified $\tau_{\text{had-vis}}$ passes the *tight* selection can be written as:

$$N_{\text{m}}^{\text{T}} = p_{\text{m}} N_{\text{m}} = \frac{p_{\text{m}} p_{\text{r}}}{p_{\text{r}} - p_{\text{m}}} N_{\text{L}} + \frac{p_{\text{m}}(p_{\text{r}} - 1)}{p_{\text{r}} - p_{\text{m}}} N_{\text{T}}. \tag{4.5}$$

The final values of p_{r} and p_{m} are parameterised in terms of the number of charged-particle tracks in the core cone ($\Delta R \leq 0.2$) and the number of charged-particle tracks in the hollow isolation cone ($0.2 < \Delta R < 0.4$) around the $\tau_{\text{had-vis}}$ axis [54], as well as the p_{T} and $|\eta|$ of the $\tau_{\text{had-vis}}$. Correlations between the variables used for parameterisation are found to have a negligible effect on the results of the method.

The probability p_{r} is determined using true $\tau_{\text{had-vis}}$ in simulated $t\bar{t}$ events in the signal region. The probability p_{m} is measured in a W+jets control region in data. Events in this control region are triggered by a combined trigger requiring an electron with $E_{\text{T}} > 18\,\text{GeV}$ or a muon with $p_{\text{T}} > 15\,\text{GeV}$ in addition to a $\tau_{\text{had-vis}}$. In both cases, the $\tau_{\text{had-vis}}$ trigger object has a p_{T} threshold of 20 GeV. The control region must have exactly one trigger-matched reconstructed electron or muon, in addition to a trigger-matched, reconstructed, *loose* $\tau_{\text{had-vis}}$. The control region is also required to have zero b-tagged jets and $m_{\text{T}}(e/\mu, E_{\text{T}}^{\text{miss}}) > 50\,\text{GeV}$ (using eq. (4.1), with the $\tau_{\text{had-vis}}$ replaced by the electron or muon). The contamination from correctly reconstructed $\tau_{\text{had-vis}}$ (7%) and electrons or muons mis-reconstructed as $\tau_{\text{had-vis}}$ (5%) is subtracted using simulation. Signal processes contribute negligibly to this region ($< 0.1\%$).

Having computed the identification and misidentification efficiencies p_{r} and p_{m}, every event in the *loose* sample is given a weight w as follows, in order to estimate the background with a misidentified $\tau_{\text{had-vis}}$ in the *tight* sample:

- for an event with a *loose but not tight* $\tau_{\text{had-vis}}$, $w_{\text{L}} = \dfrac{p_{\text{m}} p_{\text{r}}}{p_{\text{r}} - p_{\text{m}}}$;
- for an event with a *tight* $\tau_{\text{had-vis}}$, $w_{\text{T}} = \dfrac{p_{\text{m}}(p_{\text{r}} - 1)}{p_{\text{r}} - p_{\text{m}}}$.

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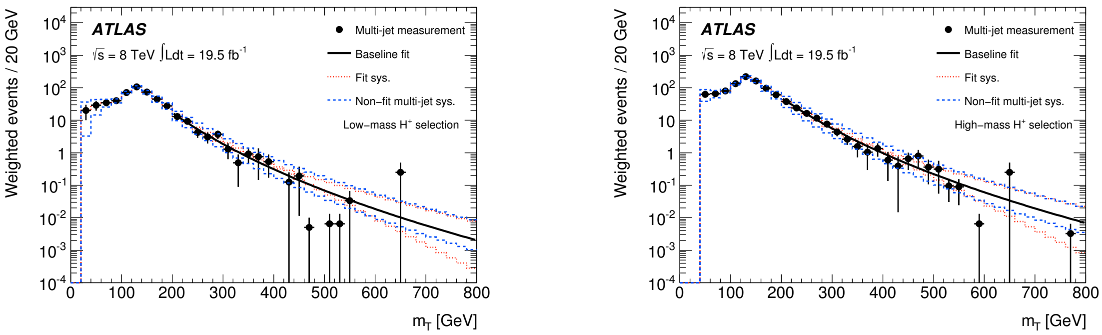


(a) Low-mass H^+ selection.

(b) High-mass H^+ selection.

Figure 3. The multi-jet background predictions from data-driven methods for the (a) low-mass and (b) high-mass H^+ event selections, with the results of fits using the power-log function, are shown in the solid line. The dotted lines show the systematic uncertainty from the choice of the fit function. The dashed lines show the total combined fits from the sources of systematic uncertainty listed in table 4.

Events with jets misidentified as $\tau_{\text{had-vis}}$ are a major background in the high-m_{T} region ($>$ 300 GeV low-mass and $>$ 400 GeV high-mass), but this region has less than one expected event per 20 GeV bin. This limitation is circumvented by fitting the m_{T} distribution using a power-log function in the mass range 200–800 GeV. The power-log function is defined by the following formula:

$$f(x) = x^{a+b\ln(x)}, \tag{4.6}$$

where a and b are fitted constants. The resulting m_{T} distribution after considering each systematic uncertainty is fitted separately. An additional systematic uncertainty is added for the choice of fit function, by symmetrising the difference between the baseline fit and an alternative fit using an exponential function. The exponential is chosen to probe the effect on the expected yield in the poor statistics tail region, since it also describes the multi-jet background well in the region with many events. Figure 3 shows the fits obtained in the nominal case, for the systematic uncertainty due to the chosen fit function, and for all other systematic uncertainties related to this background estimation (see section 5.2).

4.4 Backgrounds with electrons or muons misidentified as $\tau_{\text{had-vis}}$

Backgrounds that arise from events where an electron or muon is misidentified as $\tau_{\text{had-vis}}$ are heavily suppressed by dedicated veto algorithms, so that these events only contribute at the level of 1–2% to the total background. These backgrounds are estimated from simulated events, and they include contributions from $t\bar{t}$, single top-quark, diboson, W+jets and Z+jets processes. Leptons from in-flight decays in multi-jet events are accounted for in the multi-jet background estimate.

4.5 $\tau_{\text{had-vis}}+E_{\text{T}}^{\text{miss}}$ triggers

The analysis presented in this paper relies on $\tau_{\text{had-vis}}+E_{\text{T}}^{\text{miss}}$ triggers. To correct for any difference between the trigger efficiencies observed in simulation and those observed in data,

p_{T}^{τ}- and $E_{\mathrm{T}}^{\mathrm{miss}}$-dependent correction factors are derived, whose evaluation is limited by statistical uncertainties. To increase the sample size, the $\tau_{\text{had-vis}}$ and $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiencies are determined separately and residual effects due to correlations are taken into account as systematic uncertainties. To measure the efficiencies, a tag-and-probe method is used in a control region enriched with $t\bar{t}$ events with a μ+τ_{had} selection using a muon trigger with a p_{T} threshold of 24 GeV or 36 GeV. The trigger efficiencies are fitted separately for events with a $\tau_{\text{had-vis}}$ that has one or three charged-particle tracks. The p_{T}^{τ} ($E_{\mathrm{T}}^{\mathrm{miss}}$) trigger efficiencies are fitted in the range of 20–100 (20–500) GeV. The ratios of the fitted functions for data and simulation are then applied to the simulated samples as continuous correction factors.

Since no trigger information is available in the embedded sample, trigger efficiencies are applied to that sample. The efficiencies for the $\tau_{\text{had-vis}}$ trigger derived as described above need to be corrected for misidentified $\tau_{\text{had-vis}}$. The fraction of events with a misidentified $\tau_{\text{had-vis}}$ is substantial in the $\mu + \tau_{\text{had}}$ sample used for the tag-and-probe method, leading to a lower efficiency than in a sample with only events that have a true $\tau_{\text{had-vis}}$. Since only events with a true $\tau_{\text{had-vis}}$ are present in the embedded sample, the efficiencies determined from data are corrected by the ratio of the simulated efficiency for true $\tau_{\text{had-vis}}$ to the simulated efficiency for the $\mu + \tau_{\text{had}}$ sample.

4.6 Event yields after the event selection

The expected numbers of background events and the results from data, together with an expectation from signal contributions in the low-mass and high-mass H^+ selections, are shown in table 2. For the low-mass H^+ search, the signal contribution is shown for a cross section corresponding to $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to \tau\nu) = 0.9\%$, and for the high-mass H^+ search a possible signal contribution in the $m_h^{\max}$ scenario of the MSSM with $\tan\beta = 50$ is shown.

The number of events with a true τ_{had} is derived from the number of embedded events and does not depend on the theoretical cross section of the $t\bar{t} \to b\bar{b}W^+W^-$ process. However, this analysis does rely on the theoretical inclusive $t\bar{t}$ production cross section $\sigma_{t\bar{t}} = 253^{+13}_{-15}$ pb [30] for the estimation of the small background with electrons or muons misidentified as $\tau_{\text{had-vis}}$.

5 Systematic uncertainties

5.1 $\tau_{\text{had-vis}}$+$E_{\mathrm{T}}^{\mathrm{miss}}$ triggers

Systematic uncertainties on the measurement of the $\tau_{\text{had-vis}}$+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiencies arise from multiple sources: the selection of the muon in the μ+τ_{had} sample, the number of misidentified $\tau_{\text{had-vis}}$, the choice of fitting function, slightly varying trigger requirements during the data-taking period, a residual correlation between the $\tau_{\text{had-vis}}$ and $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers, and the effect of the $\tau_{\text{had-vis}}$ energy correction on the trigger efficiency. The dominant systematic uncertainty, which arises from misidentified $\tau_{\text{had-vis}}$ in the $t\bar{t} \to \mu\tau_{\text{had}} + X$ control region, is evaluated by measuring the trigger correction factors after varying the expected misidentified $\tau_{\text{had-vis}}$ yield by its uncertainty. These uncertainties are relevant for background events with leptons misidentified as $\tau_{\text{had-vis}}$ as well as true τ_{had} and signal

Sample	Low-mass H^+ selection	High-mass H^+ selection
True $\tau_{\rm had}$ (embedding method)	$2800 \pm 60 \pm 500$	$3400 \pm 60 \pm 400$
Misidentified jet $\to \tau_{\rm had\text{-}vis}$	$490 \pm 9 \pm 80$	$990 \pm 15 \pm 160$
Misidentified $e \to \tau_{\rm had\text{-}vis}$	$15 \pm 3 \pm 6$	$20 \pm 2 \pm 9$
Misidentified $\mu \to \tau_{\rm had\text{-}vis}$	$18 \pm 3 \pm 8$	$37 \pm 5 \pm 8$
All SM backgrounds	$3300 \pm 60 \pm 500$	$4400 \pm 70 \pm 500$
Data	3244	4474
H^+ ($m_{H^+} = 130\,\mathrm{GeV}$)	$230 \pm 10 \pm 40$	
H^+ ($m_{H^+} = 250\,\mathrm{GeV}$)		$58 \pm 1 \pm 9$

Table 2. Expected event yields after all selection criteria and comparison with $19.5\,\mathrm{fb}^{-1}$ of data. The values shown for the signal correspond to the previously published upper limit on $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to \tau\nu) = 0.9\%$ [18] for the low-mass signal point and $\tan\beta = 50$ in the MSSM $m_h^{\rm max}$ scenario for the high-mass signal point. The predicted yield for the low-mass signal selection assumes a $t\bar{t}$ cross section of 253 pb. Both the statistical and systematic uncertainties (section 5) are shown, in this order.

Source of uncertainty	Low-mass H^+ selection	High-mass H^+ selection
Muon selection	$< 1\%$	$< 1\%$
Misidentified $\tau_{\rm had\text{-}vis}$	5.6%	5.7%
Fitting function	2.1%	1.8%
Trigger definition	$< 1\%$	$< 1\%$
Residual correlations	1.4%	3.2%
$\tau_{\rm had\text{-}vis}$ energy scale	$< 1\%$	$< 1\%$

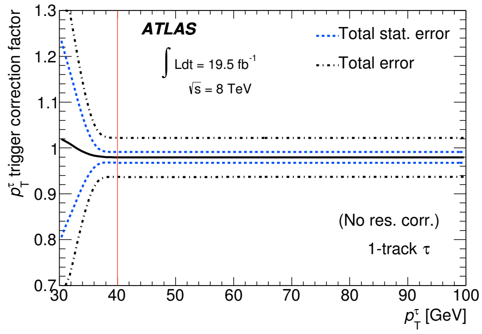
Table 3. Effect of systematic uncertainties on the combined trigger efficiencies for a low-mass ($m_{H^+} = 130\,\mathrm{GeV}$) and high-mass ($m_{H^+} = 250\,\mathrm{GeV}$) signal sample.

events. The effects on a low-mass and a high-mass signal sample are summarised in table 3 and the effect on background events with true $\tau_{\rm had}$ is shown in table 4. The trigger correction factors used to account for differences between the efficiencies in simulation and data are shown in figure 4.

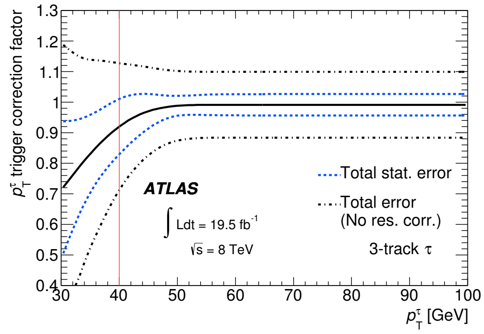
5.2 Data-driven background estimation

The systematic uncertainties arising from the data-driven methods used to estimate the various backgrounds are summarised in table 4.

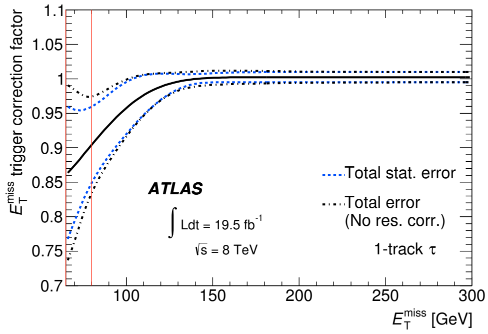
The systematic uncertainties affecting the estimation of the backgrounds with true $\tau_{\rm had}$, discussed in section 4.2, consist of the potential bias introduced by the embedding method itself (embedding parameters, evaluated by varying the amount of energy that is subtracted when removing calorimeter deposits of the muon in the original event), uncertainties from the trigger efficiency measurement as discussed in section 5.1, uncertainties



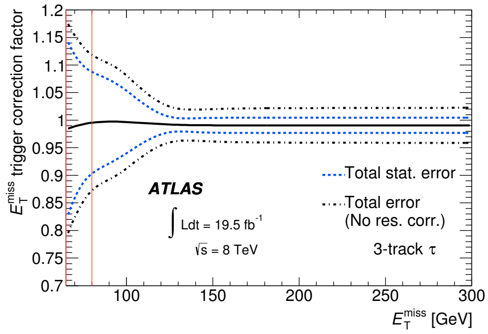
(a) 1-track $\tau_{\text{had-vis}}$, $\tau_{\text{had-vis}}$ trigger.



(b) 3-track $\tau_{\text{had-vis}}$, $\tau_{\text{had-vis}}$ trigger.



(c) 1-track $\tau_{\text{had-vis}}$, $E_{\mathrm{T}}^{\text{miss}}$ trigger.



(d) 3-track $\tau_{\text{had-vis}}$, $E_{\mathrm{T}}^{\text{miss}}$ trigger.

Figure 4. Inclusive $\tau_{\text{had-vis}}$ and $E_{\mathrm{T}}^{\text{miss}}$ trigger correction factors obtained from the ratio of functions fitted to data and simulation for $\tau_{\text{had-vis}}$ with (a, c) one and (b, d) three charged tracks are shown at the top and bottom, respectively. The vertical line on the $\tau_{\text{had-vis}}$ trigger correction factor plots indicates the lowest p_{T}^{τ} threshold used in the analysis. The vertical line on the $E_{\mathrm{T}}^{\text{miss}}$ trigger correction factor plots shows the lower boundary used in the high-mass charged Higgs boson search. The total statistical uncertainty is indicated with the dotted line and the systematic uncertainty is added in quadrature to the statistical error (dashed-dotted line). For $\tau_{\text{had-vis}}$ trigger efficiencies, the total systematic uncertainty is shown, while for the $E_{\mathrm{T}}^{\text{miss}}$ trigger efficiency, the systematic uncertainty related to residual correlations between $\tau_{\text{had-vis}}$ and $E_{\mathrm{T}}^{\text{miss}}$ is not included, since the effect is evaluated separately for several signal mass ranges and background samples.

due to a possible contamination from multi-jet events (evaluated by varying the muon isolation requirements), uncertainties associated with the simulated τ_{had} ($\tau_{\text{had-vis}}$ energy scale and identification efficiency) and uncertainties on the normalisation. The latter are dominated by the statistical uncertainty of the selected control sample and the $\tau_{\text{had-vis}}+E_{\mathrm{T}}^{\text{miss}}$ trigger efficiency uncertainties.

For the estimation of backgrounds with jets misidentified as $\tau_{\text{had-vis}}$, discussed in section 4.3, the dominant systematic uncertainties on the misidentification probability are the statistical uncertainty due to the control sample size and uncertainties due to the difference in the jet composition (gluon- or quark-initiated) between the control and signal regions. The uncertainty arising from differences in jet composition is evaluated from the difference in shape and normalisation that arises when p_{m} is measured in a control region that is

Source of uncertainty	Low-mass H^+ selection	High-mass H^+ selection
True τ_{had}		
Embedding parameters	3.0%	1.8%
Muon isolation	0.3%	2.3%
Parameters in normalisation	2.0%	2.0%
$\tau_{\text{had-vis}}$ identification	2.2%	2.0%
$\tau_{\text{had-vis}}$ energy scale	4.0%	3.6%
$\tau_{\text{had-vis}} + E_{\mathrm{T}}^{\mathrm{miss}}$ trigger	8.3%	8.3%
Jet $\to \tau_{\text{had-vis}}$		
Statistical uncertainty on p_{m}	2.0%	3.4%
Statistical uncertainty on p_{r}	0.5%	0.5%
Jet composition	1.1%	1.9%
$\tau_{\text{had-vis}}$ identification	0.8%	0.6%
e/μ contamination	0.5%	0.7%

Table 4. Dominant systematic uncertainties on the data-driven background estimates. The shift in event yield is given relative to the total background.

enriched in events with gluon-initiated jets. This control region differs from the signal region only by inverting the b-tag and $E_{\mathrm{T}}^{\mathrm{miss}}$ requirements. Other uncertainties are due to the statistical uncertainty on p_{r}, the effect of the uncertainty in the simulated true $\tau_{\text{had-vis}}$ identification efficiency on the measurement of p_{r} and p_{m}, and the effect of the simulated electron veto efficiency for true electrons on the measurement of p_{m}.

5.3 Detector simulation

Systematic uncertainties originating from the simulation of pile-up and object reconstruction are considered for signal events and background events with leptons misidentified as $\tau_{\text{had-vis}}$. This background is roughly 1% of the final background in both the low-mass and high-mass searches, so the systematic uncertainties have little effect on the final results.

Uncertainties related to the $\tau_{\text{had-vis}}$ energy scale and identification efficiency are also taken into account. The uncertainty on the identification is in the range 2−3% for $\tau_{\text{had-vis}}$ with one charged track and 3−5% for $\tau_{\text{had-vis}}$ with three charged tracks. It has been measured in data using a tag-and-probe method [54]. The $\tau_{\text{had-vis}}$ energy scale is measured with a precision of 2−4% [67]. It is determined by fitting the reconstructed visible mass of $Z \to \tau\tau$ events in data. Uncertainties related to jet or b-tagged jet energy scale, energy resolution, flavour identification and calibration, and the effects of pile-up interactions are also taken into account [68, 69], as well as uncertainties related to the reconstruction of $E_{\mathrm{T}}^{\mathrm{miss}}$ [70].

The impact of most sources of systematic uncertainty is assessed by re-applying the selection cuts for each analysis after varying a particular parameter by its ±1 standard

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deviation uncertainty. The dominant instrumental systematic uncertainties include the jet energy scale, the $\tau_{\text{had-vis}}$ energy scale, and $\tau_{\text{had-vis}}$ identification. All instrumental systematic uncertainties are taken into account for the reconstruction of $E_{\mathrm{T}}^{\mathrm{miss}}$.

These uncertainties affect all simulated samples, i.e. the signal and the background contribution with leptons misidentified as $\tau_{\text{had-vis}}$. Since the τ_{had} in the embedded samples are simulated, all τ_{had}-related uncertainties are relevant for the background with true τ_{had} as well.

5.4 Generation of $t\bar{t}$ and signal events

In order to estimate the systematic uncertainties arising from the $t\bar{t}$ and low-mass signal generation, as well as from the parton shower model, the acceptance is computed for $t\bar{t}$ events produced with MC@NLO interfaced to HERWIG/JIMMY and POWHEG interfaced to PYTHIA 8. Also, an uncertainty on the theoretical cross section, including both the factorisation/renormalisation scale and parton distribution function uncertainties, is taken into account for $t\bar{t}$ backgrounds with a lepton misidentified as a $\tau_{\text{had-vis}}$ and low-mass signal samples. The estimate of the small background with electrons or muons misidentified as $\tau_{\text{had-vis}}$ relies additionally on the theoretical inclusive $t\bar{t}$ production cross section $\sigma_{t\bar{t}} = 253^{+13}_{-15}$ pb [30].

The generator modelling uncertainties for the high-mass signal samples are estimated from a comparison between events produced with MC@NLO interfaced to HERWIG++ [71] and POWHEG interfaced to PYTHIA 8.

The systematic uncertainties originating from initial- and final-state parton radiation, which modify the jet production rate, are computed for $t\bar{t}$ backgrounds and applied to low-mass signal events by using $t\bar{t}$ samples generated with AcerMC interfaced to PYTHIA 6, where initial- and final-state radiation parameters are set to a range of values not excluded by the experimental data [72]. The largest relative differences with respect to the reference sample, after full event selections, are used as systematic uncertainties. For high-mass signal samples, this uncertainty is evaluated by varying factorisation/renormalisation scale parameters in the production of signal samples (QCD scale). The uncertainty due to the choice of parton distribution function has a negligible impact for both background and signal, and is not included. An additional uncertainty, arising from the difference in acceptance between 4FS and 5FS H^+ production is evaluated using dedicated signal samples that are generated at leading order with MadGraph [73] interfaced with PYTHIA 8, although the nominal signal samples are generated at NLO. The systematic uncertainties arising from the modelling of the $t\bar{t}$ and signal event generation and the parton shower, as well as from the initial- and final-state radiation, are summarised in table 5.

All of these uncertainties, except for H^+ production, affect only signal and background events where leptons are misidentified as $\tau_{\text{had-vis}}$.

6 Statistical analysis

In order to test the compatibility of the data with background-only and signal+background hypotheses, a profile log-likelihood ratio [74] is used with m_{T} as the discriminating vari-

Source of uncertainty	Normalisation uncertainty
Low-mass H^+	
Generator model ($b\bar{b}W^-H^+$)	9%
Generator model ($b\bar{b}W^+W^-$)	9%
$t\bar{t}$ cross section	6%
Jet production rate (SM and H^+) (QCD scale)	11%
High-mass H^+	
Generator model (H^+)	2–9%
Generator model (SM)	8%
$t\bar{t}$ cross section	6%
Jet production rate (H^+) (QCD scale)	1–2%
Jet production rate (SM) (QCD scale)	11%
H^+ production (4FS vs 5FS)	3–5%

Table 5. Systematic uncertainties arising from $t\bar{t}$ and signal generator modelling, and from the jet production rate. The uncertainties are shown for the $t\bar{t}$ background and the charged Higgs boson signal, for the low-mass and high-mass charged Higgs boson selections separately. The systematic uncertainty of the H^+ yield due to QCD scale and 4FS vs 5FS production was evaluated at masses of 200, 400, and 600 GeV. For all other systematic variations of the H^+ yield, all mass points were considered.

able. The statistical analysis is based on a binned likelihood function for these distributions. Systematic uncertainties in shape and normalisation, discussed in section 5, are incorporated via nuisance parameters fully correlated amongst the different backgrounds, and the one-sided profile likelihood ratio, $\tilde{q}_\mu$, is used as a test statistic. The parameter of interest, the signal-strength μ, is either $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to \tau^+\nu)$ (low-mass search) or $\sigma(pp \to \bar{t}H^+ + X) \times \mathcal{B}(H^+ \to \tau^+\nu)$ (high-mass search). Expected limits are derived using the asymptotic approximation [75].

The nuisance parameters are simultaneously fitted by means of a negative log-likelihood minimisation in both low-mass and high-mass regions in order to ensure that they are well estimated. This is shown in figure 5 for the nuisance parameters that have the largest impact on the fitted μ, denoted $\hat{\mu}$. The black dots indicate how a given nuisance parameter deviates from expectation, while the black error bars indicate how its post-fit uncertainty compares with its nominal uncertainty. In both the low-mass and high-mass searches, the black dots and error bars indicate respectively that none of the nuisance parameters deviate by more than one standard deviation and that their uncertainties are not underestimated. The blue hatched box shows the deviations of the fitted signal-strength parameter after changing a specific nuisance parameter upwards or downwards by its post-fit uncertainty.

The results in figure 5 indicate the relative impact of the systematic uncertainties in the statistical analysis of the low-mass and high-mass searches. For the low-mass search,

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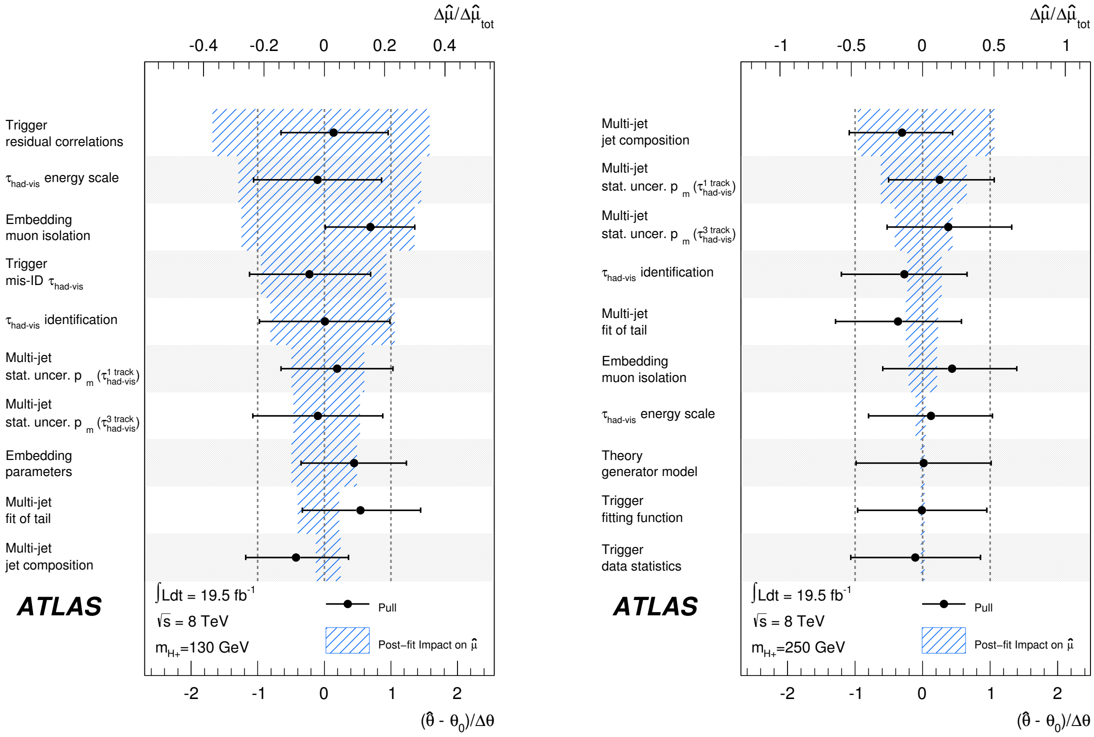


(a) Low-mass H^+ selection.

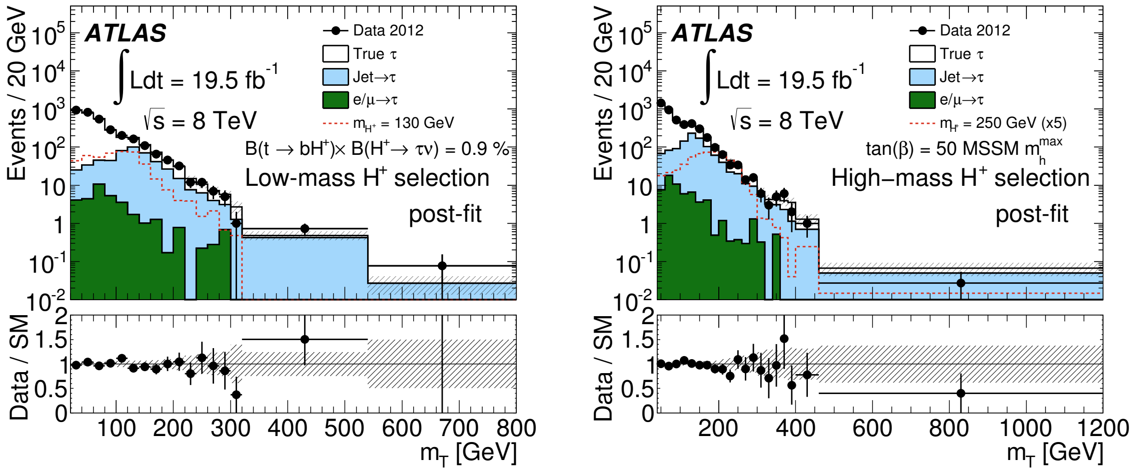
(b) High-mass H^+ selection.

Figure 5. Impact of systematic uncertainties on the final observed limits for (a) $m_{H+} = 130\,\text{GeV}$ and (b) $m_{H+} = 250\,\text{GeV}$. The systematic uncertainties are ordered (top to bottom) by decreasing impact on the fitted signal strength parameter. The dots, which refer to the bottom horizontal axis, show how each fitted nuisance parameter, $\hat{\theta}$, deviates from its nominal value, θ_0, in terms of standard deviations with respect to its nominal uncertainty, $\Delta\theta$. The solid lines indicate the post-fit uncertainties of each nuisance parameter, also relative to their nominal values. The hatched band, referring to the top horizontal axis, shows the deviations of the fitted signal-strength parameter after changing a specific nuisance parameter upwards or downwards by its post-fit uncertainty ($\Delta\hat{\mu}$) as a fraction of the total uncertainty of the fitted signal-strength parameter ($\Delta\hat{\mu}_{\text{tot}}$).

the most important systematic uncertainties are those related to the measurement of the trigger efficiency and to the simulation of the detector response to $\tau_{\text{had-vis}}$. Since the low-mass search is dominated by the presence of backgrounds with a true τ_{had}, this is consistent with expectations. For the high-mass search, the most important systematic uncertainties are due to jets misidentified as $\tau_{\text{had-vis}}$, including both the yield and m_{T} distribution of such events, and the next dominant effect is from the true $\tau_{\text{had-vis}}$ background.

7 Results

In figure 6, the m_{T} distribution after the final fit is shown. No significant deviation of the data from the SM prediction is observed. For the low-mass charged Higgs boson search, exclusion limits are set on the branching ratio $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to \tau^+\nu)$. For the high-mass H^+ search, exclusion limits are set on $\sigma(pp \to \bar{t}H^+ + X) \times \mathcal{B}(H^+ \to \tau^+\nu)$, and



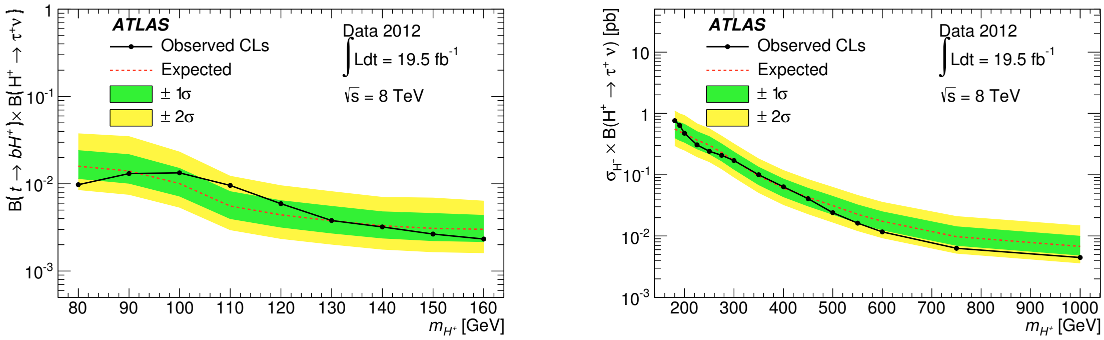
(a) Low-mass H^+ selection.

(b) High-mass H^+ selection.

Figure 6. Distributions of m_{T} after all selection criteria. The hatched area shows the total post-fit uncertainty for the SM backgrounds. For the (a) low-mass selection, bins are 20 GeV wide up to $m_{\mathrm{T}} = 320$ GeV, then 320–540 GeV and > 540 GeV. For the (b) high-mass selection, bins are 20 GeV wide up to $m_{\mathrm{T}} = 400$ GeV, then 400–460 GeV and > 460 GeV. All bins are normalised to a 20 GeV bin width. For the low-mass search (a), a possible signal contribution with $m_{H^+} = 130$ GeV, and $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to \tau^+\nu) = 0.9\%$ is overlaid on top of the SM contributions. For the high-mass search (b), a possible signal contribution with $m_{H^+} = 250$ GeV and $\tan\beta = 50$ in the $m_h^{\max}$ scenario of the MSSM, where the corresponding cross section [77] is scaled up by a factor of five, is overlaid on the SM contributions.

are to be understood as applying to the total production cross section times branching ratio of H^+ and H^- combined. Using the binned log-likelihood described in section 6, all exclusion limits are set by rejecting the signal hypothesis at the 95% confidence level (CL) using the CL$_s$ procedure [76]. These limits are based on the asymptotic distribution of the test statistic [75]. The exclusion limits are shown in figure 7a for the low-mass search and in figure 7b for the high-mass search. Expected and observed limits agree well and are within the uncertainties over the whole investigated mass range. The limits are in the range between 1.3% and 0.23% for the low-mass search. For the high-mass search, they range from 0.76 pb to 4.5 fb in the mass range 180 GeV $\leq m_{H^+} \leq$ 1000 GeV.

The limits on $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to \tau^+\nu)$ for the low-mass search and on $\sigma(pp \to \bar{t}H^+ + X) \times \mathcal{B}(H^+ \to \tau^+\nu)$ for the high-mass search are also interpreted in the context of different scenarios of the MSSM [42]. In the $m_h^{\max}$ scenario, the mass of the light CP-even Higgs boson h (m_h) is maximised. Interpreting the Higgs boson discovered at the LHC as the h, only a small region of the $m_{H^+} - \tan\beta$ parameter space in this scenario is compatible with the observation. The $m_h^{\mathrm{mod}+}$ and $m_h^{\mathrm{mod}-}$scenarios are modifications of the $m_h^{\max}$ scenario. The discovered Higgs boson is interpreted as the h as well but the requirement that m_h be maximal is dropped. This is done by reducing the amount of mixing in the top squark sector compared to the $m_h^{\max}$ scenario, leading to a larger region in the parameter space being compatible with the observation. The $m_h^{\mathrm{mod}+}$ and $m_h^{\mathrm{mod}-}$ scenarios only differ in the sign of a parameter.

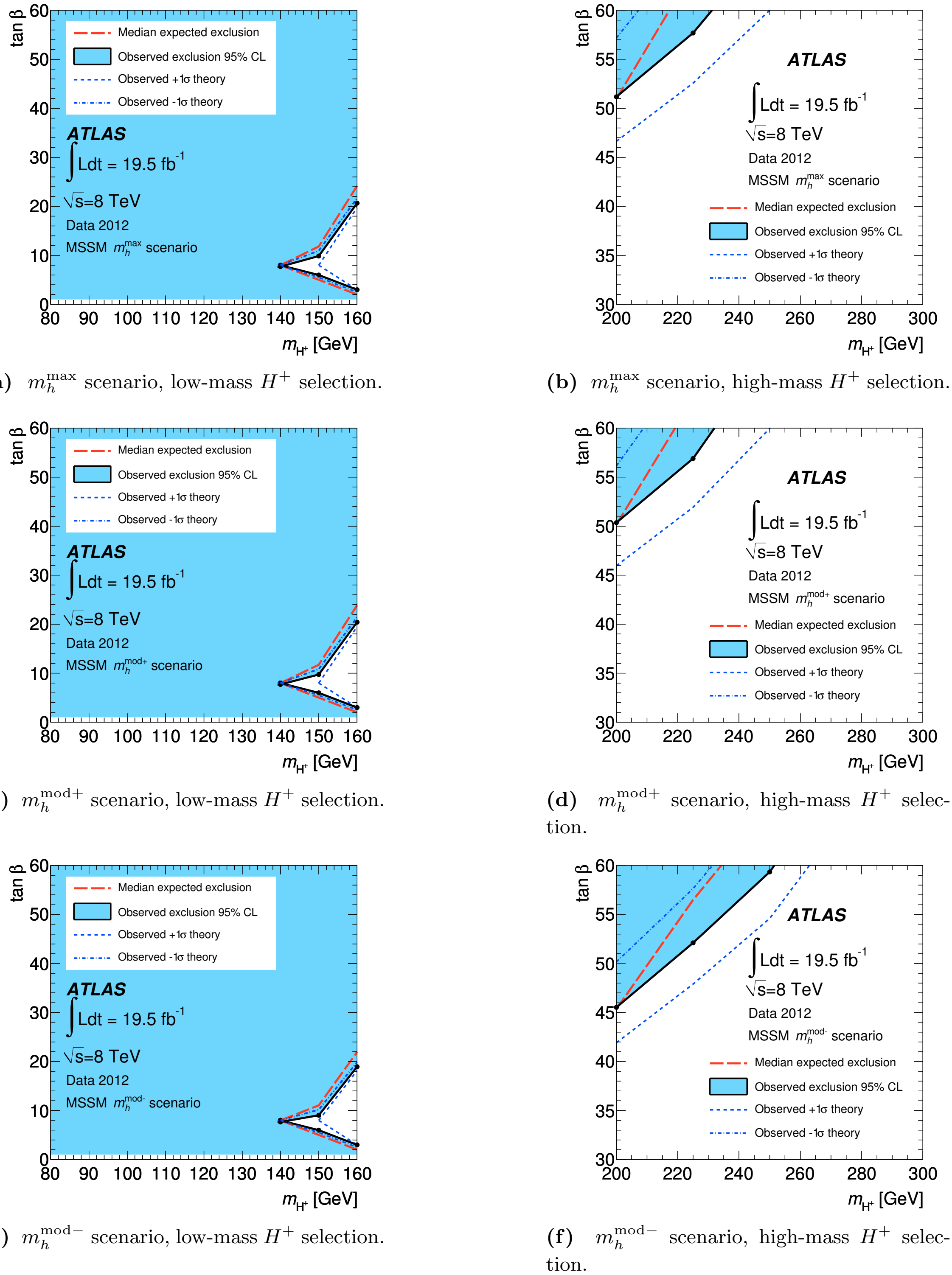


(a) Low-mass H^+ selection.

(b) High-mass H^+ selection.

Figure 7. Observed and expected 95% CL exclusion limits on the production and decay of (a) low-mass and (b) high-mass charged Higgs bosons. For the low-mass search, the limit is computed for $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to \tau^+\nu)$ for charged Higgs boson production from top-quark decays as a function of m_{H^+}. For the high-mass search, the limit is computed for $\sigma(pp \to \bar{t}H^+ + X) \times \mathcal{B}(H^+ \to \tau^+\nu)$, and is to be understood as applying to the total production cross section times branching ratio of H^+ and H^- combined.

Interpretations of the 95% CL limits in the m_h^{max}, $m_h^{\text{mod}+}$ and $m_h^{\text{mod}-}$ scenarios are shown in figure 8. In the low-mass range, almost all values for $\tan\beta > 1$ are excluded in the different scenarios, except for a small region $140\,\text{GeV} \leq m_{H^+} \leq 160\,\text{GeV}$. Values of $\tan\beta$ larger than $45 - 50$ are excluded in a mass range of $200\,\text{GeV} \leq m_{H+} \leq 250\,\text{GeV}$. The exclusions in several additional scenarios, not shown here, were also considered. In the light top squark, light stau and tauphobic scenarios, no significant exclusion is achieved in the high-mass search. In the low-mass search, the excluded regions in these scenarios are similar to those shown in figure 8. The limits for the low-mass H^+ search are also interpreted in the low-M_H scenario, where $m_{H^+} \approx 130$ GeV. Instead of excluding areas in the m_{H^+}–$\tan\beta$ plane, limits are interpreted in the $\tan\beta$–μ plane, for $300\,\text{GeV} < \mu < 3500\,\text{GeV}$ and $1.5 < \tan\beta < 9.5$, where μ is the higgsino mass parameter. This model is excluded everywhere where it is tested and where it is well-defined. For the interpretation of the low-mass search, the following relative theoretical uncertainties on $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to \tau^+\nu)$ are considered [78–80]: 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 to the running b-quark mass [81]. These uncertainties are added linearly, as recommended by the LHC Higgs cross section working group [79]. For the interpretation of the high-mass search, separate uncertainties are included for the 4FS and 5FS calculations [82]. For the 5FS calculation, the following theoretical uncertainties are taken into account: scale uncertainties of approximately 10–20% that vary with m_{H^+}, the combined uncertainty on the parton distribution function, mass of the b-quark, and strong coupling of approximately 10–15%. For the 4FS calculation, only a scale uncertainty of approximately 30% is taken into account. Owing to the complication arising from the overlap and interference with off-shell $t\bar{t}$ production in the mass range of $m_{H^+} = 180$–$200\,\text{GeV}$, the MSSM interpretation is shown only for $m_{H^+} \geq 200\,\text{GeV}$.



(a) $m_h^{\rm max}$ scenario, low-mass H^+ selection.

(b) $m_h^{\rm max}$ scenario, high-mass H^+ selection.

(c) $m_h^{\rm mod+}$ scenario, low-mass H^+ selection.

(d) $m_h^{\rm mod+}$ scenario, high-mass H^+ selection.

(e) $m_h^{\rm mod-}$ scenario, low-mass H^+ selection.

(f) $m_h^{\rm mod-}$ scenario, high-mass H^+ selection.

Figure 8. The 95% CL exclusion limits on $\tan\beta$ as a function of m_{H^+}. Results are shown in the context of different benchmark scenarios of the MSSM for the regions in which reliable theoretical predictions exist. Results are shown for (low-mass, high-mass) H^+ search in the (a, b) $m_h^{\rm max}$, (c, d) $m_h^{\rm mod+}$ and (e, f) $m_h^{\rm mod-}$ scenarios in the left (right) column.

8 Conclusions

Charged Higgs bosons decaying via $H^+ \to \tau^+\nu$ are searched for in $t\bar{t}$ events, in the decay mode $t \to bH^+$ (low-mass search), and for H^+ production in association with a top quark, $pp \to tH^+ + X$ (high-mass search). The analysis makes use of a total of 19.5 fb^{-1} of pp collision data at $\sqrt{s} = 8$ TeV, recorded in 2012 with the ATLAS detector at the LHC. The final state considered in this search is characterised by the presence of a hadronic τ decay, missing transverse momentum, b-tagged jets, a hadronically decaying W boson, as well as the absence of any electrons or muons. Data-driven methods are employed to estimate the dominant background contributions. The data are found to be in agreement with the SM predictions. Upper limits at the 95% confidence level are set on the branching ratio $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to \tau^+\nu)$ between 0.23% and 1.3% for a mass range of $m_{H^+} = 80$–160 GeV, a major improvement over the previous published limits of 0.8–3.4% for the mass range of $m_{H^+} = 90$–160 GeV [18, 19]. For the mass range of $m_{H^+} = 180$–1000 GeV, the first upper limits from ATLAS are set for the production cross section times branching ratio, $\sigma(pp \to \bar{t}H^+ + X) \times \mathcal{B}(H^+ \to \tau^+\nu)$, between 0.76 pb and 4.5 fb. Interpreted in the context of the $m_h^{\max}$, $m_h^{\text{mod}+}$ and $m_h^{\text{mod}-}$ scenarios of the MSSM, the entire parameter space with $\tan\beta > 1$ is excluded for the low-mass range 90 GeV $\leq m_{H^+} \leq$ 140 GeV, and almost all of the parameter space with $\tan\beta > 1$ is excluded for 140 GeV $\leq m_{H^+} \leq$ 160 GeV. For the high-mass range 200 GeV $\leq m_{H^+} \leq$ 250 GeV, a region of parameter space with high $\tan\beta$ is excluded.

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