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Search for the Standard Model Higgs boson in the $H \to \tau^+\tau^-$ decay mode in $\sqrt{s} = 7$ TeV pp collisions with ATLAS

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Abstract: A search for the Standard Model Higgs boson decaying into a pair of τ leptons is reported. The analysis is based on a data sample of proton-proton collisions collected by the ATLAS experiment at the LHC and corresponding to an integrated luminosity of $4.7\,\mathrm{fb}^{-1}$. No significant excess over the expected background is observed in the Higgs boson mass range of 100–150 GeV. The observed (expected) upper limits on the cross section times the branching ratio for $H \to \tau^+\tau^-$ are found to be between 2.9 (3.4) and 11.7 (8.2) times the Standard Model prediction for this mass range.

Keywords: Hadron-Hadron Scattering

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1 Introduction

The Higgs boson is the only fundamental particle in the Standard Model (SM) of particle physics that has not yet been observed. It is predicted by the Higgs mechanism [1–6], which in the SM gives mass to particles. The search for the Higgs boson is a centrepiece of the Large Hadron Collider (LHC) physics programme.

An indirect constraint on the Higgs boson mass of $m_H < 185\,\text{GeV}$ at the 95% confidence level (CL) has been set using global fits to electroweak precision data [7]. Direct searches at LEP and the Tevatron have placed exclusion limits at 95% CL for $m_H < 114.4\,\text{GeV}$ and in the region $147\,\text{GeV} < m_H < 179\,\text{GeV}$ [8, 9], respectively. The results of searches in various channels using data corresponding to an integrated luminosity of up to $5\,\text{fb}^{-1}$ have recently been reported by both the ATLAS and CMS Collaborations [10, 11] excluding the mass range between 112.9 GeV and 115.5 GeV and the region between 127 GeV and 600 GeV, again at the 95% CL.

In the Higgs boson mass range 100–150 GeV, the $H \to \tau^+\tau^-$ decay mode is a promising channel for the search at the LHC with branching ratios between 8% and 1.8%. The $H \to \tau^+\tau^-$ search is complementary to searches with other decays in the same mass range and enhances the overall sensitivity. Also, if the Higgs boson is discovered, the measurement of the $H \to \tau^+\tau^-$ decay rate provides a test of the SM prediction for the τ Yukawa coupling.

The process with the largest cross section to produce a SM Higgs boson at the LHC is gluon fusion $gg \to H$. However, Higgs boson production via vector boson (WW, ZZ) fusion $qq \to qqH$ (VBF) and via Higgs-strahlung $qq \to VH$, in association with a hadronically decaying vector boson ($V = W$ or Z), are highly relevant as well because they lead to additional jets in the final state, which provide distinct experimental signatures. In particular the VBF topology of two high-energy jets with a large rapidity separation offers a good discrimination against background processes. For all production processes above, the Higgs boson is typically more boosted in the transverse plane if there are additional high-p_{T} jets in the event, which increases the transverse momentum of the τ decay products and thus facilitates the measurement of the $\tau^+\tau^-$ invariant mass and the discrimination of the signal from background processes.

This paper presents SM Higgs boson searches in the $H \to \tau^+_{\text{lep}}\tau^-_{\text{lep}}$, $H \to \tau^+_{\text{lep}}\tau^-_{\text{had}}$, and $H \to \tau^+_{\text{had}}\tau^-_{\text{had}}$ channels,[1] where τ_{lep} and τ_{had} denote leptonically and hadronically decaying τ leptons, respectively. The data analyses use proton-proton (pp) collisions at $\sqrt{s} = 7$ TeV collected by the ATLAS experiment in 2011, which correspond to an integrated luminosity of $4.7\,\text{fb}^{-1}$.

In order to enhance the sensitivity of the search, the selected events are analysed in several separate categories according to the number and topology of reconstructed jets.

2 Data and Monte Carlo simulated samples

The ATLAS detector is a multipurpose apparatus with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle [12]. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and an external muon spectrometer incorporating three large superconducting air-core toroid magnets.

Electrons, muons, τ leptons and jets can be reconstructed and identified in the ATLAS detector.[2] Only data taken with all sub-systems relevant to this analysis operational are used. This results in an integrated luminosity of $4.7\,\text{fb}^{-1}$ for the full 2011 data sample.

[1] Charge-conjugated decay modes are implied. Throughout the remainder of the paper, a simplified notation without the particle charges is used.

[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 beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

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The signal contributions considered here include the gluon fusion production process, the VBF production process, and the Higgs-strahlung VH production in association with a hadronically-decaying vector boson $V = W, Z$. For the decay of the Higgs boson, the $H \to \tau\tau$ mode is considered. Next-to-next-to-leading-order (NNLO) Quantum Chromodynamics (QCD) corrections, soft-gluon resummations calculated in the next-to-next-to-leading-log-approximation and next-to-leading-order (NLO) electroweak (EW) corrections are applied to the signal cross sections for the $gg \to H$ production process [13–24]. The cross sections of the VBF process are calculated with full NLO QCD and electroweak corrections [25–27], and approximate NNLO QCD corrections [28]. The WH/ZH processes are calculated with NNLO QCD corrections [29, 30] and NLO EW radiative corrections are applied [31]. The Higgs boson decay branching ratios are calculated using HDECAY [32]. The $gg \to H$ and VBF processes are modelled using the POWHEG [33, 34] Monte Carlo (MC) generator, interfaced to PYTHIA [35] for showering and hadronisation. In the $gg \to H$ process, the Higgs boson p_{T} spectrum is reweighted to agree with the prediction of the HqT program [36]. The associated VH production process is modelled using PYTHIA.

ALPGEN [37], interfaced to HERWIG [38], with the MLM matching scheme [39] is used to model the production of single W and Z/γ^* bosons decaying to charged leptons in association with jets. MC@NLO [40] is used to model $t\bar{t}$, WW, WZ and ZZ production processes, using HERWIG for the parton shower and hadronisation and JIMMY [41] for the underlying event modelling. AcerMC [42] is used to model single top-quark production for all three production channels (s-channel, t-channel, and Wt production).

The TAUOLA [43] and PHOTOS [44] programs are used to model the decay of τ leptons and the Quantum Electrodynamics (QED) radiation of photons, respectively.

The set of parton distribution functions (PDF) CT10 [45] is used for the MC@NLO samples, as well as CTEQ6L1 [46] for the ALPGEN samples, and MRST2007 [47] for the PYTHIA and HERWIG samples. Acceptances and efficiencies are based on a simulation of the ATLAS detector using GEANT4 [48, 49]. Since the data are affected by the detector response to multiple interactions (pileup) occurring in the same or nearby bunch crossings, the simulation includes a treatment of the event pileup conditions present in the 2011 data.

The $Z/\gamma^* \to \tau\tau$ background processes are modelled with a τ-embedded $Z/\gamma^* \to \mu\mu$ data sample as described in section 6.

3 Selection and reconstruction of physics objects

Electron candidates are formed from an energy deposit in the electromagnetic calorimeter and associated to a track measured in the inner detector. They are selected if they have a transverse energy $E_{\mathrm{T}} > 15\,\mathrm{GeV}$, lie within $|\eta| < 2.47$ but outside the transition region between the barrel and end-cap calorimeters ($1.37 < |\eta| < 1.52$), and meet quality requirements based on the expected shower shape [50].

Muon candidates are formed from a track measured in the inner detector and linked to a track in the muon spectrometer [51]. They are required to have a transverse momentum $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and to lie within $|\eta| < 2.5$. Additionally, the difference between the z-position of the point of closest approach of the muon inner detector track to the beam-line and the z-coordinate of the primary vertex is required to be less than 1 cm.[3] This requirement reduces

[3]The primary vertex is defined as the vertex with the largest $\sum p_T^2$ of the associated tracks.

the contamination due to cosmic ray muons and beam-induced backgrounds. Muon quality criteria based on, e.g., inner detector hit requirements are applied in order to achieve a precise measurement of the muon momentum and reduce the misidentification rate.

Identified electrons and muons are required to be isolated: the additional transverse energy in the electromagnetic and hadronic calorimeters must be less than 8% (4%) of the electron transverse energy (muon transverse momentum) in a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around the electron (muon) direction. The sum of the transverse momenta of all tracks with p_{T} above 1 GeV located within a cone of radius $\Delta R = 0.4$ around the electron (muon) direction and originating from the same primary vertex must be less than 6% of the electron transverse energy (muon transverse momentum).

Jets are reconstructed using the anti-k_{t} algorithm [52] with a distance parameter value of $R = 0.4$, taking as input three-dimensional noise-suppressed clusters in the calorimeters. Reconstructed jets with $p_{\mathrm{T}} > 20$ GeV and within $|\eta| < 4.5$ are selected. The reconstructed jet energy is calibrated using p_{T} - and η-dependent correction factors based on MC simulation and validated with data [53]. Events are discarded if a jet is associated with out-of-time activity or calorimeter noise. After having associated tracks to jets by requiring $\Delta R < 0.4$ between tracks and the jet direction, a jet-vertex fraction (JVF) is computed for each jet as the scalar p_{T} sum of all associated tracks from the primary vertex divided by the scalar p_{T} sum of all tracks associated with the jet. Conventionally, JVF $= -1$ is assigned to jets with no associated tracks. Jets with $|\eta| < 2.4$ are required to have $|\mathrm{JVF}| > 0.75$ in order to suppress pileup contributions. In the pseudorapidity range $|\eta| < 2.5$, b-jets are identified using a tagging algorithm based on the discrimination power of the impact parameter information and of the reconstruction of the displaced vertices of the hadron decays inside the jets [54]. The b-tagging algorithm has an average efficiency of 58% for b-jets in $t\bar{t}$ events [55]. The corresponding light-quark jet misidentification probability is 0.1–0.5%, depending on the jet p_{T} and η [56].

Hadronic decays of τ leptons are characterised by the presence of one or three charged hadrons accompanied by a neutrino and possibly neutral hadrons, which results in a collimated shower profile in the calorimeters and only a few nearby tracks. The visible decay products are combined into τ_{had} candidates. These candidates are reconstructed as jets, which are re-calibrated to account for the different calorimeter response to hadronic decays as compared to hadronic jets. The four-momenta of the τ_{had} candidates are reconstructed from the energy deposits in the calorimeters and the rejection of jets misidentified as hadronic τ decays is performed by a multivariate discriminator based on a boosted decision tree [57] that uses both tracking and calorimeter information. The identification is optimised to be 50% efficient while the jet misidentification probability is kept below 1%. A τ_{had} candidate must lie within $|\eta| < 2.5$, have a transverse momentum greater than 20 GeV, one or three associated tracks (with $p_{\mathrm{T}} > 1$ GeV) and a total charge of ± 1 computed from the associated tracks. Dedicated electron and muon veto algorithms are used.

When different objects selected according to the above criteria overlap with each other geometrically (within $\Delta R < 0.2$), only one of them is considered for further analysis. The overlap is resolved by selecting muon, electron, τ_{had} and jet candidates in this order of priority.

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The magnitude of the missing transverse momentum [58] ($E_{\mathrm{T}}^{\mathrm{miss}}$) is reconstructed including contributions from muon tracks and energy deposits in the calorimeters. Calorimeter cells belonging to three-dimensional noise-suppressed clusters are used and they are calibrated taking into account the reconstructed physics object to which they belong.

4 Preselection

An initial selection of events is performed by requiring a vertex from the primary pp collisions that is consistent with the beam spot position, with at least three associated tracks, each with $p_{\mathrm{T}} > 500\,\mathrm{MeV}$. Overall quality criteria are applied to suppress events with fake $E_{\mathrm{T}}^{\mathrm{miss}}$, produced by non-collision activity such as cosmic ray muons, beam-related backgrounds, or noise in the calorimeters.

The $\ell\ell$, $\ell\tau_{\mathrm{had}}$ and $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ final states[4] considered in this search are defined in a mutually exclusive way: a requirement of exactly two, one, or zero electrons or muons is imposed, respectively.

4.1 $H \to \tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$

Signal events in this channel are selected by requiring exactly two isolated and oppositely-charged light leptons (electrons and/or muons). Single lepton and di-lepton triggers are used to preselect the data. The trigger object quality requirements were tightened during the data-taking period to cope with increasing instantaneous luminosity. The single muon trigger requires $p_{\mathrm{T}} > 18$ GeV; for the single electron trigger the E_{T} threshold changes from 20 GeV to 22 GeV depending on the LHC instantaneous luminosity; the di-muon trigger requires $p_{\mathrm{T}} > 15$ GeV for the leading muon and $p_{\mathrm{T}} > 10$ GeV for the sub-leading muon; the di-electron trigger requires $E_{\mathrm{T}} > 12$ GeV for each of the two electrons; the $e\mu$ trigger requires $E_{\mathrm{T}} > 10$ GeV for the electron and $p_{\mathrm{T}} > 6$ GeV for the muon. In addition to the trigger requirements, the preselection requires $E_{\mathrm{T}} > 22\,\mathrm{GeV}$ if the electron satisfies only the single electron trigger. The E_{T} requirement is increased to 24 GeV when the trigger threshold is 22 GeV. If a muon is associated only with the single muon trigger object, it is required to have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$. For the $e\mu$ channel the di-lepton invariant mass is required to be in the range of 30 GeV $< m_{\ell\ell} <$ 100 GeV, whereas for the ee and $\mu\mu$ channels 30 GeV $< m_{\ell\ell} <$ 75 GeV is required, reducing the contamination from $Z/\gamma^* \to \ell\ell$.

4.2 $H \to \tau_{\mathrm{lep}}\tau_{\mathrm{had}}$

Signal events in this channel are characterised by exactly one isolated light lepton ℓ, a τ_{had} candidate, and large $E_{\mathrm{T}}^{\mathrm{miss}}$ due to the undetected neutrinos. For the $e\tau_{\mathrm{had}}$ ($\mu\tau_{\mathrm{had}}$) final states, events are preselected using the single electron (muon) trigger described in section 4.1. Exactly one electron with $E_{\mathrm{T}} > 25$ GeV or one muon with $p_{\mathrm{T}} > 20$ GeV, and one oppositely-charged τ_{had} candidate with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ are required in the event. Events with more than one electron or muon candidate are rejected to suppress events from

[4] Here ℓ denotes an electron or a muon (also referred to below as light leptons).

$Z/\gamma^* \to \ell^+\ell^-$ decays and from $t\bar{t}$ or single top-quark production.[5] The transverse mass of the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ is calculated as

$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}\,, \tag{4.1}$$

where p_{T}^{ℓ} denotes the magnitude of the transverse momentum of the lepton and $\Delta\phi$ is the angle between the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ directions in the plane perpendicular to the beam direction. In order to reduce contributions from the W+jets and $t\bar{t}$ background processes, only events with $m_{\mathrm{T}} < 30\,\mathrm{GeV}$ are considered for further analysis. In addition, $E_{\mathrm{T}}^{\mathrm{miss}}$ is used for further event selection and categorisation, as described in section 5.

4.3 $H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$

Signal events in this channel are characterised by two identified hadronic τ decays and large $E_{\mathrm{T}}^{\mathrm{miss}}$ from the undetected neutrinos. The corresponding event selection starts with a double hadronic τ trigger, where the p_{T} thresholds are 29 GeV and 20 GeV for the leading and sub-leading hadronic τ objects, respectively, which is designed to detect hadronic τ objects with high efficiency [59]. The trigger decision combines the two hadronic τ trigger objects with the asymmetric p_{T} threshold of 29 GeV and 20 GeV, respectively, to suppress the jet background. A requirement of exactly zero charged light leptons, as defined in section 3, is imposed. Two identified opposite charge τ_{had} candidates with $p_{\mathrm{T}} > 35$ GeV and $p_{\mathrm{T}} > 25$ GeV are required, each matching a τ trigger object [59].

5 Analysis categories

For further analysis, the selected event samples are split into several categories according to the number and topology of reconstructed jets. The sensitivity of the search is usually higher for categories where the presence of one or more jets is required, as discussed in section 1, but events without any reconstructed high-p_{T} jets are also considered in order to maximise the sensitivity.

5.1 $H \to \tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$

Four categories defined by their jet multiplicity and kinematics are used for this channel: H +2-jet VBF, H +2-jet VH, H +1-jet and H +0-jet. The first two categories require the presence of at least two jets and the cuts are optimised in one case for the VBF process [60–62], and in the other for the VH and $gg \to H$ processes [63].

The H +0-jet category uses an inclusive selection to collect part of the signal not selected by the categories with jets. In the H +0-jet category, only the $e\mu$ final state is considered because of the overwhelming $Z/\gamma^* \to \ell\ell$ background in the ee and $\mu\mu$ final states. In order to reduce the $t\bar{t}$ background, it is required that the di-lepton azimuthal opening angle be $\Delta\phi_{\ell\ell} > 2.5\,\mathrm{rad}$ and that the leptonic transverse energy be

[5] For the purpose of vetoing additional light leptons, the isolation requirements are removed from the muon selection and a looser identification requirement is used for electrons. The transverse momentum (energy) threshold for muons (electrons) is lowered to 10 GeV (15 GeV).

$H_T^{\rm lep} = p_T^{\ell 1} + p_T^{\ell 2} + E_T^{\rm miss} < 120$ GeV, where $p_T^{\ell 1}$ and $p_T^{\ell 2}$ are the magnitudes of the transverse momenta of the leading and sub-leading leptons, respectively.

In categories with jets (H +2-jet VBF, H +2-jet VH and H +1-jet), the presence of a hadronic jet with a transverse momentum $p_T > 40$ GeV is required and, to suppress the $t\bar{t}$ background, the event is rejected if any jet with $p_T > 25$ GeV is identified as a b-jet. In addition, $E_T^{\rm miss} > 40$ GeV ($E_T^{\rm miss} > 20$ GeV) for the $ee, \mu\mu$ ($e\mu$) channels is also required.

The collinear approximation technique [64] is used to reconstruct the kinematics of the $\tau\tau$ system. The approximation is based on two assumptions: that the neutrinos from each τ decay are nearly collinear with the corresponding visible τ decay products and that the $E_T^{\rm miss}$ in the event is due only to neutrinos. In this case, the total invisible momentum carried away by neutrinos in each τ decay can be estimated from the polar and azimuthal angles of the visible products of each τ decay. Then, the invariant mass of the $\tau\tau$ system can be calculated as $m_{\tau\tau} = m_{\ell\ell}/\sqrt{x_1 \cdot x_2}$, where x_1 and x_2 are the momentum fractions of the two τ candidates carried away by their visible decay products. Events that do not satisfy $0.1 < x_1, x_2 < 1.0$ are rejected. In categories with jets, there is an additional requirement that $0.5\,\mathrm{rad} < \Delta\phi_{\ell\ell} < 2.5\,\mathrm{rad}$ to suppress the $Z/\gamma^* \to \ell\ell$ background.

For the H +2-jet categories, a subleading jet with $p_T > 25$ GeV is required in addition. For the H +2-jet VBF category, a pseudorapidity difference between the two selected jets of $\Delta\eta_{jj} > 3$ and a di-jet invariant mass of $m_{jj} > 350$ GeV are required. Finally, the event is rejected in the H +2-jet VBF category if any additional jet with $p_T > 25$ GeV and $|\eta| < 2.4$ is found in the pseudorapidity range between the two leading jets.

For the H +2-jet VH category, the requirement on the pseudorapidity separation of the jets and on the di-jet invariant mass are instead: $\Delta\eta_{jj} < 2$ and 50 GeV $< m_{jj} <$ 120 GeV.

Only events failing the cuts for the H +2-jet categories are considered in the H +1-jet category. For the H +1-jet category, the invariant mass of the two τ leptons and the leading jet is required to fulfil $m_{\tau\tau j} > 225$ GeV, where the τ momenta are taken from the collinear approximation. The main Higgs production mechanism in this category is the $gg \to H$ process plus a high-p_T parton.

The $m_{\tau\tau}$ calculated with the collinear approximation ("collinear mass") is used in categories with jets. Because this variable displays poor resolution in the H +0-jet category due to the back-to-back configuration of the two leptons, the effective mass ($m_{\tau\tau}^{\rm eff}$), defined as the invariant mass of the two leptons and the $E_T^{\rm miss}$, is used instead.

5.2 $H \to \tau_{\rm lep}\tau_{\rm had}$

The selected data are split into seven categories based on jet properties and $E_T^{\rm miss}$.

The H +2-jet VBF category includes all selected events with $E_T^{\rm miss} > 20$ GeV and at least two jets with $p_T > 25$ GeV, where the two leading jets are found in opposite hemispheres of the detector ($\eta_{jet1} \cdot \eta_{jet2} < 0$), with $\Delta\eta_{jj} > 3$ and $m_{jj} > 300$ GeV. Both the lepton and the $\tau_{\rm had}$ candidate are required to be found in the pseudorapidity range between the two leading jets. Due to the limited size of the selected event samples, the VBF category combines the $e\tau_{\rm had}$ and $\mu\tau_{\rm had}$ final states.

Two $H+1$-jet categories include all selected events with $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV and at least one jet with $p_{\mathrm{T}} > 25$ GeV, that fail the VBF selection. The $e\tau_{\mathrm{had}}$ and $\mu\tau_{\mathrm{had}}$ final states are considered separately.

Four $H+0$-jet categories include all selected events without any jet with $p_{\mathrm{T}} > 25$ GeV. The $e\tau_{\mathrm{had}}$ and $\mu\tau_{\mathrm{had}}$ final states are considered separately. In addition, the analysis is separated into events with $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV and $E_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV. The low-$E_{\mathrm{T}}^{\mathrm{miss}}$ region is included here because, in the absence of high-p_{T} jets, the Higgs decay products, including the neutrinos, are typically less boosted than for events with additional jet activity.

For each category, the mass of the $\tau\tau$ system is reconstructed using the Missing Mass Calculator (MMC) [65]. This technique provides a full reconstruction of event kinematics in the $\tau\tau$ final state with 99% efficiency and 13–20% resolution in $m_{\tau\tau}$, depending on the event topology (better resolution is obtained for events with high-p_{T} jets). Conceptually, the MMC is a more sophisticated version of the collinear approximation. The main improvement comes from requiring that relative orientations of the neutrinos and other decay products are consistent with the mass and kinematics of a τ lepton decay. This is achieved by maximising a probability defined in the kinematically allowed phase space region.

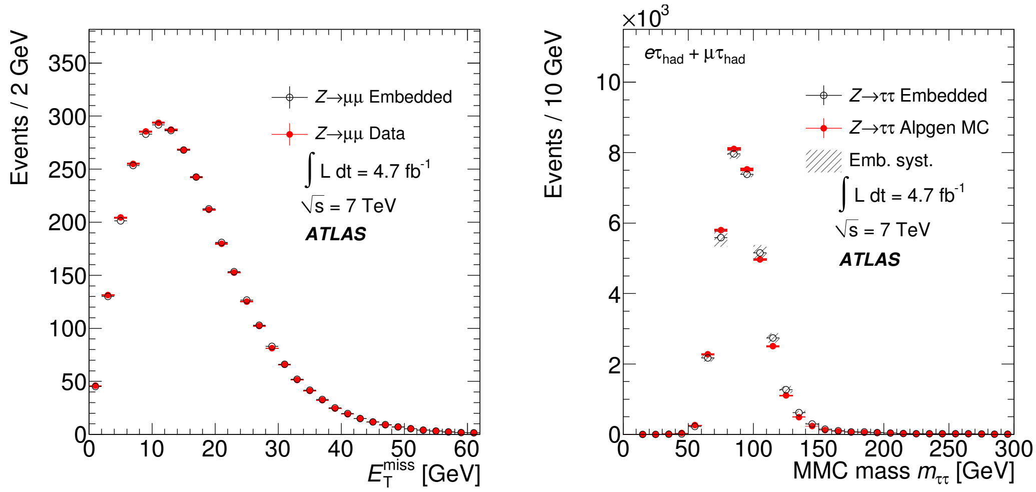
5.3 $H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$

In the $H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel, only a single $H+1$-jet category is defined. After selecting two hadronic τ candidates, the collinear mass approximation cuts $0 < x_1, x_2 < 1$ are applied. Events at this stage are used as a control sample to derive the normalisation of the $Z/\gamma^* \to \tau\tau$ background. Then, events are selected if $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV and if the leading jet has a transverse momentum $p_{\mathrm{T}} > 40$ GeV. The two τ candidates are required to be separated by $\Delta R(\tau,\tau) < 2.2$. Also, only events with an invariant mass of the $\tau\tau$ pair and the leading jet $m_{\tau\tau j} > 225$ GeV are considered for further analysis. The event selection criteria described here are effective against the multi-jet and $Z/\gamma^* \to \tau\tau$ backgrounds. The collinear mass approximation is used for the Higgs mass reconstruction.

6 Background estimation and modelling

The background composition and normalisation are determined using data-driven methods and the simulated event samples described in section 2.

The main background to the Higgs boson signal in all selected final states is the largely irreducible $Z/\gamma^* \to \tau\tau$ process. While it is not possible to select a Higgs signal-free $Z/\gamma^* \to \tau\tau$ sample directly from the data, this background is still modelled in a data-driven way, by choosing a control sample where the expected signal contamination is negligible. In a sample of selected $Z/\gamma^* \to \mu\mu$ data events, the muon tracks and associated calorimeter cells are replaced by τ leptons from a simulated $Z/\gamma^* \to \tau\tau$ decay with the same kinematics, where the τ polarisation and spin correlations are modelled with the TAUOLA program and the τ-μ mass difference is taken into account as well. Thus, only the τ decays and the corresponding detector response are taken from the simulation, whereas the underlying event kinematics and all other properties — including pileup effects — are obtained from the data. These embedded data are used to model the shape of the relevant $Z/\gamma^* \to \tau\tau$ background



(a) E_T^{miss} .　　**(b)** Invariant mass $m_{\tau\tau}$.

Figure 1. (a) E_T^{miss} distributions for the $Z/\gamma^* \to \mu\mu$ data before and after muon embedding and (b) MMC mass distributions (defined in section 5) for the τ-embedded $Z/\gamma^* \to \mu\mu$ data and simulated $Z/\gamma^* \to \tau\tau$ events. For (a) only statistical uncertainties are shown; (b) also includes systematic uncertainties associated with the embedding procedure as discussed in section 7.

distributions as well as the efficiency for selecting $Z/\gamma^* \to \tau\tau$ events from the preselected sample. The overall normalisation at the preselection level is obtained from simulation.

The procedure is extensively validated: example results for the $H \to \tau_{\rm lep}\tau_{\rm had}$ channel are shown in figure 1. Systematic effects intrinsic to the method are studied by replacing the muons selected in data by simulated muons instead of τ decays. Figure 1(a) shows a comparison of the E_T^{miss} distributions from the selected $Z/\gamma^* \to \mu\mu$ events in data before and after this muon embedding, demonstrating that the embedding procedure does not introduce any significant bias to the reconstruction of the event properties. Figure 1(b) compares the MMC mass distributions reconstructed from the τ-embedded $Z/\gamma^* \to \mu\mu$ data and simulated $Z/\gamma^* \to \tau\tau$ events after the preselection described in section 4; good agreement is found and similar studies for the other channels yield the same conclusions.

6.1 $H \to \tau_{\rm lep}\tau_{\rm lep}$

The $Z/\gamma^* \to \tau\tau$ background is modelled using the embedding procedure described above. The contribution from $Z/\gamma^* \to \ell^+\ell^-$ is determined by scaling the yields in the Monte Carlo simulation using correction factors obtained by comparing data to simulation in low- and high-E_T^{miss} control regions enriched in these backgrounds. The correction factors are obtained separately for $Z/\gamma^* \to ee$ and $Z/\gamma^* \to \mu\mu$ and for the different analysis categories and are on the order of 10%.

The fake lepton background consists of events that have a reconstructed lepton that did not originate from the decay of a τ lepton or the leptonic decay of a W or Z boson. The normalisation and shape of relevant distributions are obtained from data with a template method using a control region in which the lepton isolation requirement is reversed. The chosen template shape is the p_T distribution of the sub-leading lepton. For this method to

	$ee+\mu\mu+e\mu$ H +2-jet VBF	$ee+\mu\mu+e\mu$ H +2-jet VH	$ee+\mu\mu+e\mu$ H +1-jet	$e\mu$ H +0-jet
$gg\to H$ signal	0.26±0.06±0.10	0.8 ±0.1 ±0.2	3.9 ±0.2 ±1.0	23 ±1 ±3
VBF H signal	1.08±0.03±0.11	0.10±0.01±0.01	1.15±0.03±0.01	0.75±0.03±0.06
VH signal	0.01±0.01±0.01	0.53±0.02±0.07	0.40±0.02±0.03	0.52±0.02±0.04
$Z/\gamma^*\to\tau^+\tau^-$	24 ± 3 ± 2	107 ±12 ± 9	$(0.52\pm0.01\pm0.04)\cdot10^3$	$(9.68\pm0.05\pm0.07)\cdot10^3$
$Z/\gamma^*\to\ell^+\ell^-$ (ℓ=e,μ)	2 ± 1 ± 1	25 ± 4 ± 9	83 ±10 ±30	185 ±11 ±14
$t\bar{t}$+single top	7 ± 1 ± 2	42 ± 2 ± 6	98 ± 3 ±12	169 ± 4 ±14
$WW/WZ/ZZ$	0.9± 0.3± 0.3	6 ± 1 ± 1	21 ± 1 ± 3	221 ± 3 ±18
Fake leptons	1.3± 0.8± 0.6	13 ± 2 ± 5	30 ± 4 ±12	$(1.2\pm0.5)\cdot10^3$
Total background	35 ± 3 ± 4	193 ± 7 ±20	$(0.75\pm0.01\pm0.05)\cdot10^3$	$(11.4\pm0.5)\cdot10^3$
Observed data	27	185	702	11420

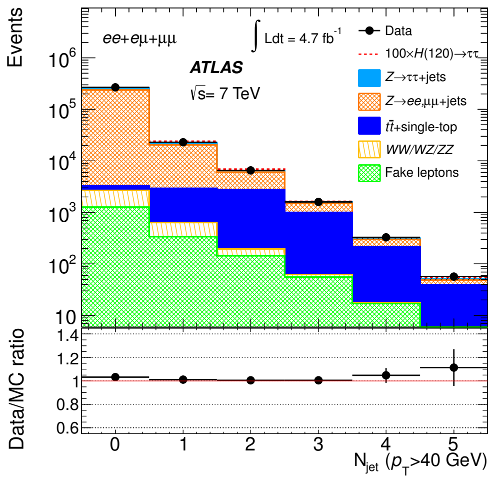
Table 1. Number of events after the $H\to\tau_{\rm lep}\tau_{\rm lep}$ selection for the four categories in data and predicted number of background events, for an integrated luminosity of 4.7 fb^{-1}. Expectations for the Higgs boson signal ($m_H=120$ GeV) are also given. Statistical and systematic uncertainties are quoted, in that order.

be applied, it is first verified that the template shapes of the fake lepton distribution in the control and signal regions agree within uncertainties. This is performed at intermediate steps of the event selection where the data sample is dominated by background events and where the number of expected signal events is negligible.

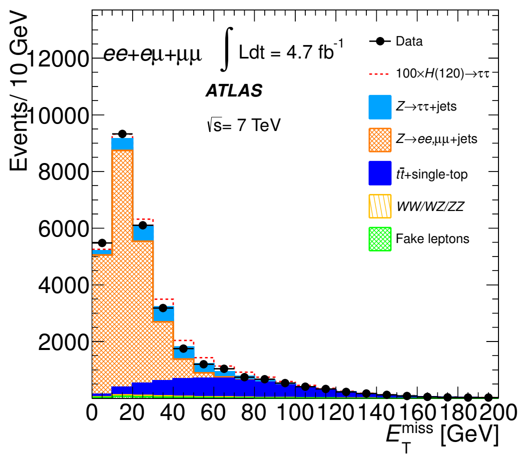
After subtracting the simulated backgrounds, the template shape in a given distribution is obtained from the control region, while the normalisation is obtained from a fit of the distribution of the events in the signal region with the template shape. The uncertainty related to the estimation of backgrounds with fake leptons is calculated from the uncertainty on the subtraction of other processes from Monte Carlo simulation and from the difference in the $p_{\rm T}$ shape of the events in the control region and signal regions. Such systematic uncertainties lie in the range of 30–40%.

The contributions of the $t\bar{t}$, single top-quark and electroweak di-boson backgrounds are estimated from simulation. The Monte Carlo description of the top-quark backgrounds has been validated using data by selecting control regions enriched in top-quark background processes. The control regions are defined by inverting the b-jet selection for the H +2-jet VBF, H +2-jet VH, H +1-jet categories and by inverting the $H_{\rm T}^{\rm lep}$ selection for the H +0-jet category.

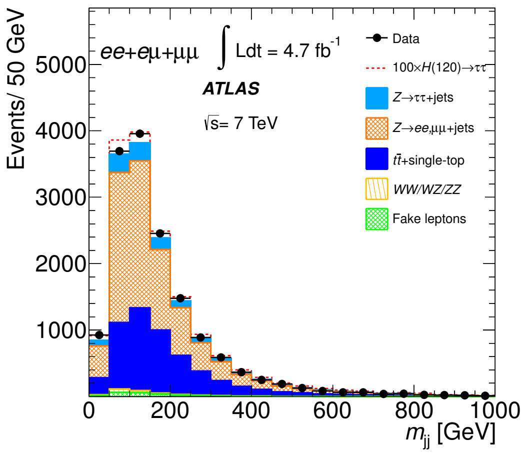
Table 1 displays the number of events expected and observed in the four categories after all selection criteria including all systematic uncertainties described in section 7. The estimated combined background contributions are found to give a good description of all quantities relevant to the analysis. As examples, the distributions of the jet multiplicity, $E_{\rm T}^{\rm miss}$, the invariant mass of the two leading jets and their pseudorapidity difference are shown in figure 2. Figure 3 displays the invariant mass spectra of the selected events for the four categories.



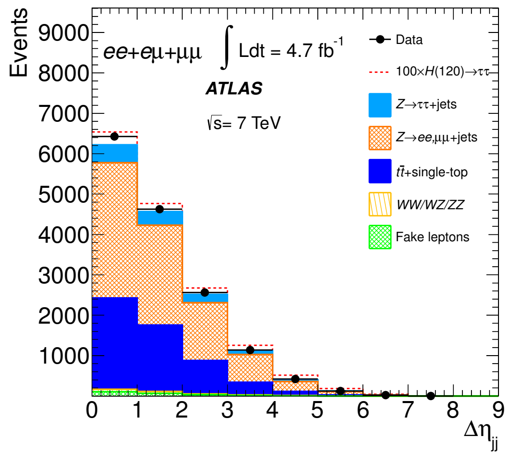
(a) Jet multiplicity ($p_T > 40\,\text{GeV}$).



(b) E_T^{miss} .

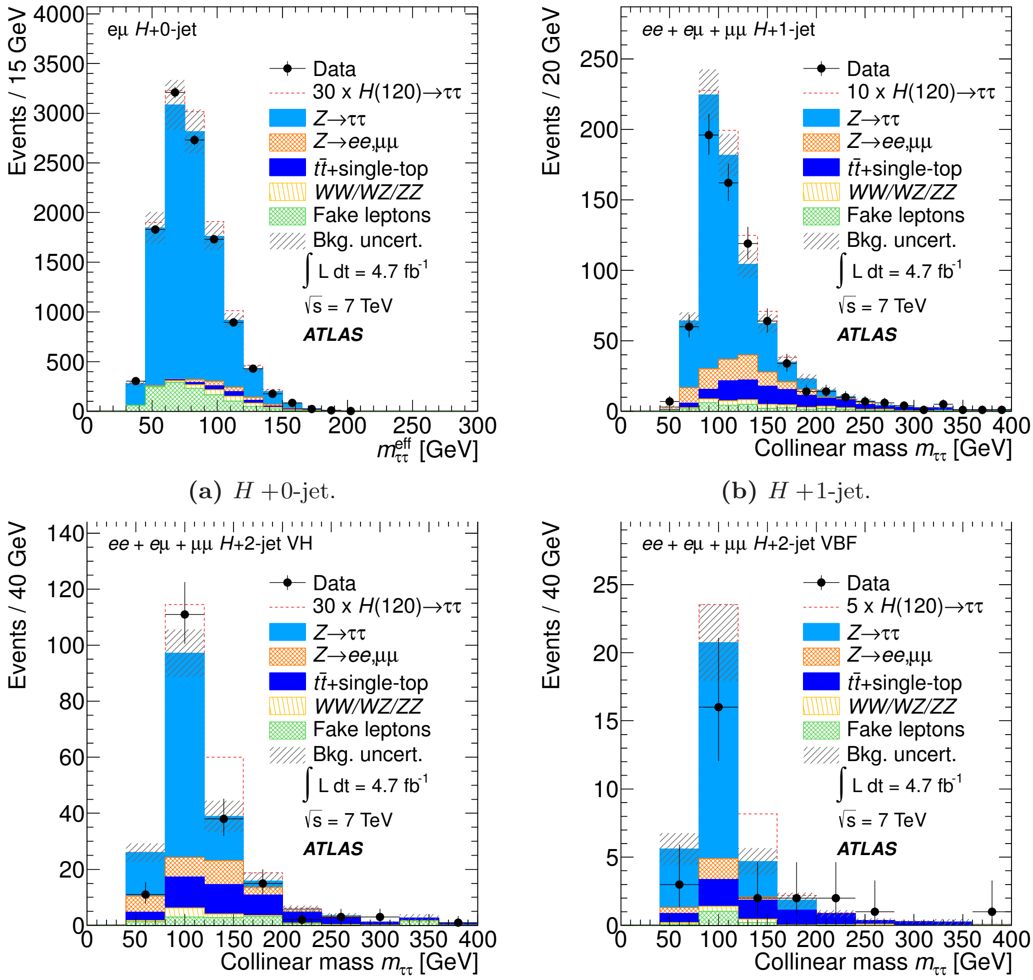


(c) Invariant mass of the two leading jets.



(d) η difference of the two leading jets.

Figure 2. Distributions of (a) the jet multiplicity, (b) the E_T^{miss}, (c) the invariant mass of the two leading jets and (d) the η difference of the two leading jets in the $H \to \tau_{\text{lep}}\tau_{\text{lep}}$ channel for the selection criteria described in the text. Simulated samples are normalised to an integrated luminosity of $4.7\,\text{fb}^{-1}$. For illustration only, the signal contributions have been scaled by factors given in the legends. 30 GeV $< m_{\ell\ell} <$ 100 GeV is required for the ee and $\mu\mu$ channels and 30 GeV $< m_{\ell\ell} <$ 75 GeV for the $e\mu$ channel. For the E_T^{miss} distribution the presence of a leading jet with $p_T > 40$ GeV is required; for the invariant mass and for the η difference of the two leading jets, the presence of a sub-leading jet with $p_T > 25$ GeV is required in addition.



(a) H +0-jet. **(b)** H +1-jet. **(c)** H +2-jet VH. **(d)** H +2-jet VBF.

Figure 3. Reconstructed $m_{\tau\tau}$ of the selected events in the $H \to \tau_{\rm lep}\tau_{\rm lep}$ channel for the four categories described in the text. Simulated samples are normalised to an integrated luminosity of $4.7\,{\rm fb}^{-1}$. Predictions from the Higgs boson signal ($m_H = 120\,{\rm GeV}$) and from backgrounds are given. In the case of the H +0-jet category $m^{\rm eff}_{\tau\tau}$ is used. For illustration only, the signal contributions have been scaled by factors given in the legends.

6.2 $H \to \tau_{\rm lep}\tau_{\rm had}$

In order to estimate the background contributions to the selected $H \to \tau_{\rm lep}\tau_{\rm had}$ candidate events, a control sample in data is obtained by applying the signal selection described in section 5.2 but now requiring that the light lepton and the $\tau_{\rm had}$ candidate have the same charge. This control sample is referred to as the same-sign (SS) sample here, in contrast to the opposite-sign (OS) signal sample. The number of OS background events in the signal region ($n^{\rm bkg}_{\rm OS}$) can be expressed as

$$n^{\rm bkg}_{\rm OS} = n^{\rm all}_{\rm SS} + n^{W+{\rm jets}}_{\rm OS-SS} + n^{Z\to\tau\tau}_{\rm OS-SS} + n^{\rm other}_{\rm OS-SS}, \tag{6.1}$$

where $n^{\rm all}_{\rm SS}$ is the sum of all SS backgrounds in the signal region and the remaining terms are the differences between the number of OS and SS events for W + jets, $Z/\gamma^* \to \tau\tau$ and other backgrounds, respectively. Due to their large production cross sections, multi-jet processes provide a significant background if quark/gluon jets are misidentified as hadronic

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τ decays. The ratio of OS to SS events for the multi-jet background ($r^{\mathrm{QCD}}_{\mathrm{OS/SS}}$) is expected to be close to unity and therefore $n^{\mathrm{QCD}}_{\mathrm{OS-SS}} = 0$ is assumed. This assumption is validated with a control sample that is dominated by low-p_{T} jets from multi-jet processes. This sample is selected by replacing the requirement $E_{\mathrm{T}}^{\mathrm{miss}} > 20\,\mathrm{GeV}$ with $E_{\mathrm{T}}^{\mathrm{miss}} < 15\,\mathrm{GeV}$ and removing the isolation criteria of the electron or muon candidate. After subtraction of the other backgrounds using simulation, a value of $r^{\mathrm{QCD}}_{\mathrm{OS/SS}} = 1.10 \pm 0.01(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})$ is obtained. The observed deviation of $r^{\mathrm{QCD}}_{\mathrm{OS/SS}}$ from unity is taken into account as a systematic uncertainty for the final result.

The $Z/\gamma^* \to \tau\tau$ contribution is estimated from the τ-embedded $Z/\gamma^* \to \mu\mu$ sample in the data, as described previously. For the $W+$jets background, a significant deviation of the ratio of OS and SS events ($r^{W}_{\mathrm{OS/SS}}$) from unity is expected since $W+$jets production is dominated by gu/gd-processes that often give rise to a jet originating from a quark, the charge of which is anti-correlated with the W boson charge. The predicted number of $W+$jets background events is obtained from the simulation after applying a normalisation correction factor determined from W-dominated data control samples.[6] The remaining contributions $n^{\mathrm{other}}_{\mathrm{OS-SS}}$ are taken from the simulation.

Table 2 displays the number of events expected and observed in the seven categories after the full signal selection, including all systematic uncertainties as described in section 7. The estimated combined background contributions are found to give a good description of all quantities relevant to the analysis. As examples, the distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$, the transverse mass of the lepton-$E_{\mathrm{T}}^{\mathrm{miss}}$ system as well as the invariant mass of the two leading jets and their pseudorapidity difference are shown in figure 4. Figure 5 shows the corresponding $\tau\tau$ invariant mass spectra, where the electron and muon categories have been combined for illustration purposes. The data are found to be consistent with the estimated combined background contributions in both normalisation and shape within the uncertainties.

In order to validate these results, an alternative background estimation is performed. This second method provides an estimate of the multi-jet background using control samples that are defined by separately inverting the light-lepton isolation and the τ_{had}-ℓ charge correlation requirements, respectively. In addition to the signal region (A) this results in three background-dominated regions B (SS $\ell\tau_{\mathrm{had}}$, ℓ isolated), C (OS $\ell\tau_{\mathrm{had}}$, ℓ anti-isolated) and D (SS $\ell\tau_{\mathrm{had}}$, ℓ anti-isolated).

The shape of the MMC mass distribution for multi-jet contributions in the signal region A is taken from the control region B and the normalisation is derived from the relation $n_{\mathrm{A}} = n_{\mathrm{C}}/n_{\mathrm{D}} \times n_{\mathrm{B}}$. Here, n_{B}, n_{C} and n_{D} denote the event yields in regions B, C and D, after subtracting the contribution from non-multi-jet backgrounds in all control regions. The $Z/\gamma^* \to \tau\tau$ contribution is estimated from the τ-embedded $Z/\gamma^* \to \mu\mu$ data and the estimate of the $W+$jets background is obtained from the simulation after applying normalisation correction factors determined from W-dominated (high-m_{T}) OS and SS data control samples. The remaining contributions are obtained from the simulation. The resulting total background estimates are also included in table 2 and are found to be consistent with both the observed number of data events and the predictions of the default background estimate within the uncertainties.

[6]These control samples are defined by replacing the $m_{\mathrm{T}} < 30\,\mathrm{GeV}$ requirement in the nominal selection with $m_{\mathrm{T}} > 50\,\mathrm{GeV}$.

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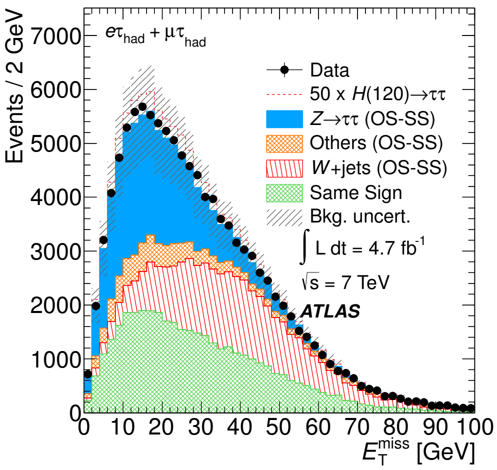
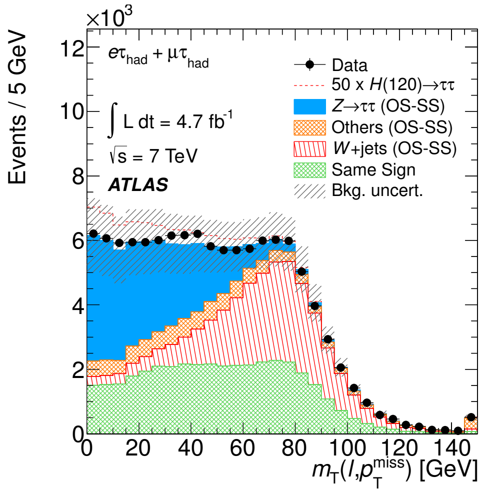
	H +0-jet (low E_T^{miss})		H +0-jet (high E_T^{miss})	
	Electron	Muon	Electron	Muon
ggH signal	$11 \pm 1 \pm 2$	$17 \pm 1 \pm 4$	$7.1 \pm 0.8 \pm 1.5$	$9.8 \pm 0.9 \pm 2.1$
VBF H signal	$0.08 \pm 0.02 \pm 0.12$	$0.11 \pm 0.03 \pm 0.03$	$0.09 \pm 0.02 \pm 0.02$	$0.14 \pm 0.03 \pm 0.03$
VH signal	$0.07 \pm 0.02 \pm 0.05$	$0.10 \pm 0.03 \pm 0.01$	$0.08 \pm 0.0\ 2 \pm 0.01$	$0.08 \pm 0.02 \pm 0.01$
n_{SS}^{all}	$(3.3 \pm 0.2 \pm 0.7) \cdot 10^3$	$(2.0 \pm 0.1 \pm 0.4) \cdot 10^3$	$(0.69 \pm 0.06 \pm 0.14) \cdot 10^3$	$(0.47 \pm 0.04 \pm 0.09) \cdot 10^3$
n_{OS-SS}^{W+jets}	$(0.33 \pm 0.02 \pm 0.04) \cdot 10^3$	$(0.50 \pm 0.02 \pm 0.07) \cdot 10^3$	$(0.15 \pm 0.01 \pm 0.02) \cdot 10^3$	$(0.18 \pm 0.01 \pm 0.03) \cdot 10^3$
$n_{OS-SS}^{Z\to\tau\tau}$	$(3.70 \pm 0.06 \pm 0.61) \cdot 10^3$	$(7.29 \pm 0.06 \pm 1.21) \cdot 10^3$	$(1.49 \pm 0.04 \pm 0.23) \cdot 10^3$	$(2.80 \pm 0.04 \pm 0.42) \cdot 10^3$
n_{OS-SS}^{other}	$(0.97 \pm 0.04 \pm 0.22) \cdot 10^3$	$(0.59 \pm 0.04 \pm 0.14) \cdot 10^3$	$(0.27 \pm 0.02 \pm 0.08) \cdot 10^3$	$(0.14 \pm 0.02 \pm 0.04) \cdot 10^3$
Total background	$(8.2 \pm 0.2 \pm 0.8) \cdot 10^3$	$(10.4 \pm 0.2 \pm 1.2) \cdot 10^3$	$(2.59 \pm 0.07 \pm 0.26) \cdot 10^3$	$(3.59 \pm 0.06 \pm 0.43) \cdot 10^3$
Observed data	8363	10911	2545	3570
Altern. estimate	$(8.7 \pm 0.1 \pm 0.8) \cdot 10^3$	$(10.7 \pm 0.1 \pm 1.0) \cdot 10^3$	$(2.76 \pm 0.05 \pm 0.33) \cdot 10^3$	$(3.75 \pm 0.05 \pm 0.47) \cdot 10^3$

	H +1-jet		H +2-jet VBF
	Electron	Muon	Electron + Muon
ggH signal	$8.1 \pm 0.7 \pm 1.6$	$10.8 \pm 0.8 \pm 2.2$	$0.9 \pm 0.2 \pm 0.3$
VBFH signal	$1.6 \pm 0.1 \pm 0.1$	$1.9 \pm 0.1 \pm 0.1$	$2.2 \pm 0.1 \pm 0.2$
VH signal	$1.1 \pm 0.1 \pm 0.1$	$1.4 \pm 0.1 \pm 0.1$	$0.02 \pm 0.01 \pm 0.01$
n_{SS}^{all}	$(0.93 \pm 0.07 \pm 0.19) \cdot 10^3$	$(0.49 \pm 0.04 \pm 0.10) \cdot 10^3$	$45 \pm 7 \pm 9$
n_{OS-SS}^{W+jets}	$(0.25 \pm 0.01 \pm 0.03) \cdot 10^3$	$(0.26 \pm 0.01 \pm 0.03) \cdot 10^3$	$5 \pm 1 \pm 2$
$n_{OS-SS}^{Z\to\tau\tau}$	$(1.23 \pm 0.03 \pm 0.17) \cdot 10^3$	$(1.76 \pm 0.03 \pm 0.25) \cdot 10^3$	$54 \pm 6 \pm 8$
n_{OS-SS}^{other}	$(0.28 \pm 0.02 \pm 0.04) \cdot 10^3$	$(0.24 \pm 0.01 \pm 0.03) \cdot 10^3$	$20 \pm 3 \pm 5$
Total background	$(2.69 \pm 0.08 \pm 0.26) \cdot 10^3$	$(2.75 \pm 0.05 \pm 0.27) \cdot 10^3$	$124 \pm 10 \pm 13$
Observed data	2610	2711	122
Altern. estimate	$(2.63 \pm 0.05 \pm 0.25) \cdot 10^3$	$(2.72 \pm 0.04 \pm 0.28) \cdot 10^3$	$131 \pm 11 \pm 23$

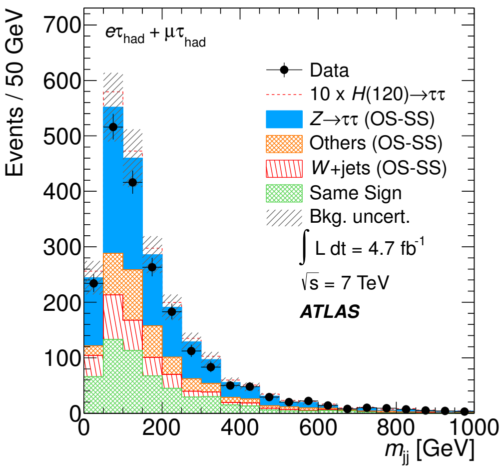
Table 2. Predicted number of signal events (for $m_H = 120\,\text{GeV}$) and predicted backgrounds obtained as described in the text, together with the observed number of events in data for the $H \to \tau_{lep}\tau_{had}$ categories. The total background yield predicted by the alternative estimation method is given as well for comparison. The listed uncertainties are statistical and systematic, in that order.



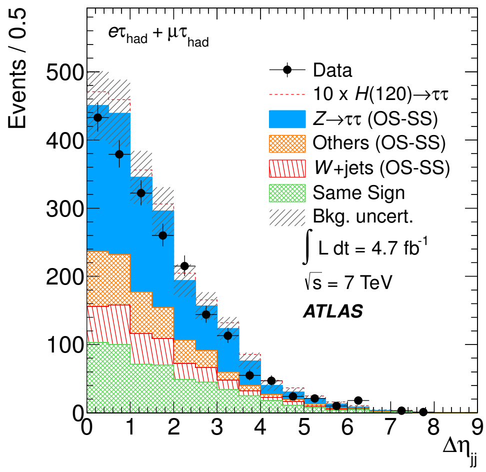
(a) $E_{\mathrm{T}}^{\mathrm{miss}}$.



(b) Transverse mass.

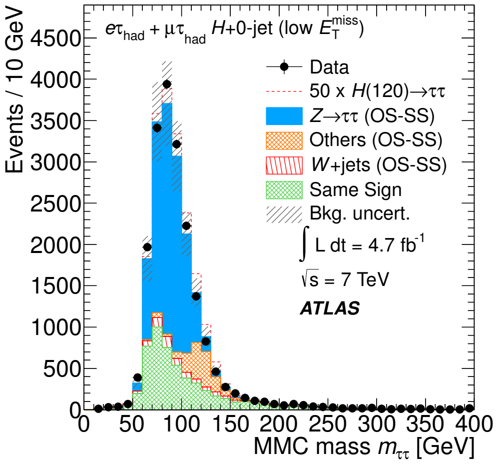


(c) Invariant mass of the two leading jets.

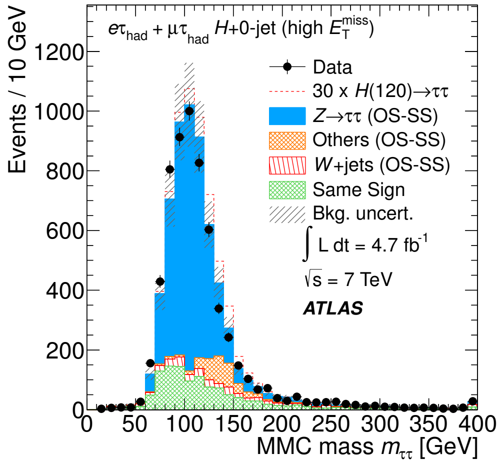


(d) η difference of the two leading jets.

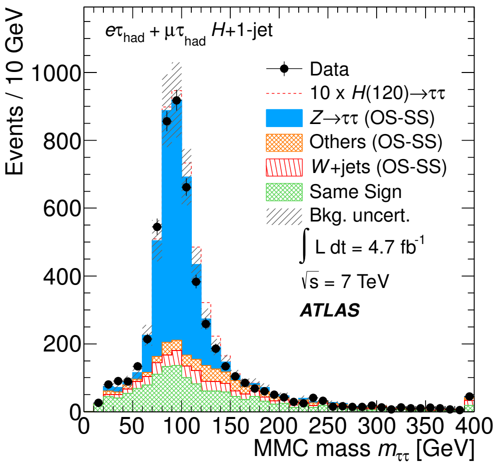
Figure 4. (a) Missing transverse momentum, (b) transverse mass of the lepton-$E_{\mathrm{T}}^{\mathrm{miss}}$ system as well as (c) invariant mass and (d) pseudorapidity difference of the two leading jets in the $H \to \tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel. The preselection criteria and an $E_{\mathrm{T}}^{\mathrm{miss}} > 20\,\mathrm{GeV}$ requirement are applied except those for the displayed quantity; for (c) and (d) the presence of at least two jets with $p_{\mathrm{T}} > 25$ GeV is required in addition. Simulated samples are normalised to an integrated luminosity of $4.7\,\mathrm{fb}^{-1}$. The selected events in data are shown together with the predicted Higgs boson signal ($m_H = 120$ GeV) stacked above the background contributions (see text). For illustration only, the signal contributions have been scaled by factors given in the legends.



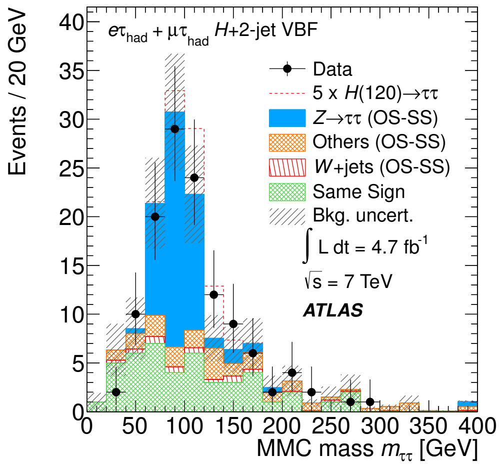
(a) Combined H +0-jet (low $E_{\mathrm{T}}^{\mathrm{miss}}$).



(b) Combined H +0-jet (high $E_{\mathrm{T}}^{\mathrm{miss}}$).



(c) Combined H +1-jet.



(d) H +2-jet VBF.

Figure 5. MMC mass (defined in section 5) distributions of the selected events in the $H \to \tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel. The corresponding electron and muon categories for the H +0-jet and H +1-jet categories are shown combined here, while in the data analysis they are considered separately. The selected events in data are shown together with the predicted Higgs boson signal ($m_H = 120$ GeV) stacked above the background contributions (see text). For illustration only, the signal contributions have been scaled by factors given in the legends.

Further studies of specific background contributions are performed by estimating the probability to misidentify jets as τ_{had} candidates in the signal region and using data control regions for the background from $t\bar{t}$ production processes. Results are consistent with the background estimates in table 2 in both cases.

6.3 $H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$

The dominant backgrounds in the $H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel are $Z/\gamma^* \to \tau\tau$ and multi-jet production. For both, the normalisation and shape of the mass distribution are estimated using data-driven methods.

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The normalisation of the $Z/\gamma^* \to \tau\tau$ background is obtained by using collision data events at an early stage of the event selection. This data-driven control sample is defined by requiring that events contain two $\tau_{\rm had}$ candidates that pass the hadronic selections including the collinear approximation cuts ($0 < x_{1,2} < 1$ and $\Delta R(\tau\tau) < 2.8$). To avoid signal contamination in this control sample, a requirement that $m_{\tau\tau} < 100\,\text{GeV}$ is applied; this results in a SM Higgs signal contamination of less than 0.2%. The $Z/\gamma^* \to \tau\tau$ contribution is obtained by fitting the track multiplicity of the two τ candidates simultaneously. The tracks associated to the $\tau_{\rm had}$ candidates are counted in the cone defined by $\Delta R < 0.6$, as motivated by the momentum correlation between tracks in $\tau_{\rm had}$ candidates [57]. A two-dimensional distribution of the track multiplicities for these two τ candidates is formed, and a track multiplicity fit is performed. The multi-jet template is modelled from the same-sign (SS) candidates in the data while the $Z/\gamma^* \to \tau\tau$ contribution is modelled by the simulation. The less significant backgrounds are estimated from the simulation and subtracted before the fit is performed. The result of the fit is used to normalise the τ-embedded $Z/\gamma^* \to \mu\mu$ sample described above, and then this sample is used to model the acceptance of the later cuts and the mass shape in the signal region.

The multi-jet contribution is estimated by the same two-dimensional track multiplicity fitting technique, where the fit is now performed in the signal region. The contribution from di-τ events is allowed to float in the fit, where the shape comes from the simulation. It is assumed that the shape of the two-dimensional track multiplicity in the $Z/\gamma^* \to \tau\tau$ and Higgs boson signal processes are the same.

The systematic uncertainties considered for the background prediction arise from the jet template statistics, alternative multi-jet track multiplicity templates, the presence of non-di-τ background, signal contamination, charge misidentification probability and variations in the pileup conditions.

Instead of using the SS events for the multi-jet track template, the alternative multi-jet track multiplicity template is built from events with one additional electron or muon which enhances the contribution of W+jets events, where two jets are misidentified as the hadronic taus. This provides a different mix of quark- and gluon-initiated jets from the inclusive multi-jet sample, addressing a possible flavour dependence of the track multiplicity distribution.

The overall systematic uncertainties are 11.6% and 22% for $Z/\gamma^* \to \tau\tau$ and multi-jet backgrounds, respectively.

The mass shape from the multi-jet events is modelled by dropping the opposite-sign and $\tau_{\rm had}$ track multiplicity requirements. In order to obtain a data sample that is enriched with the multi-jet background, events are accepted if they are same-sign events or if the sum of the charges of the products of a single τ decay is 0 or ± 2. This mass shape model is tested against several other hypothesis obtained, e.g., from pure SS samples or events selected with looser τ identification criteria.

Figure 6 shows the kinematic distributions of (a) the ΔR of the two τ candidates, (b) the missing transverse momentum, (c) the collinear mass and (d) the invariant mass of the reconstructed Higgs boson and the leading jet in the $H \to \tau_{\rm had}\tau_{\rm had}$ control region.

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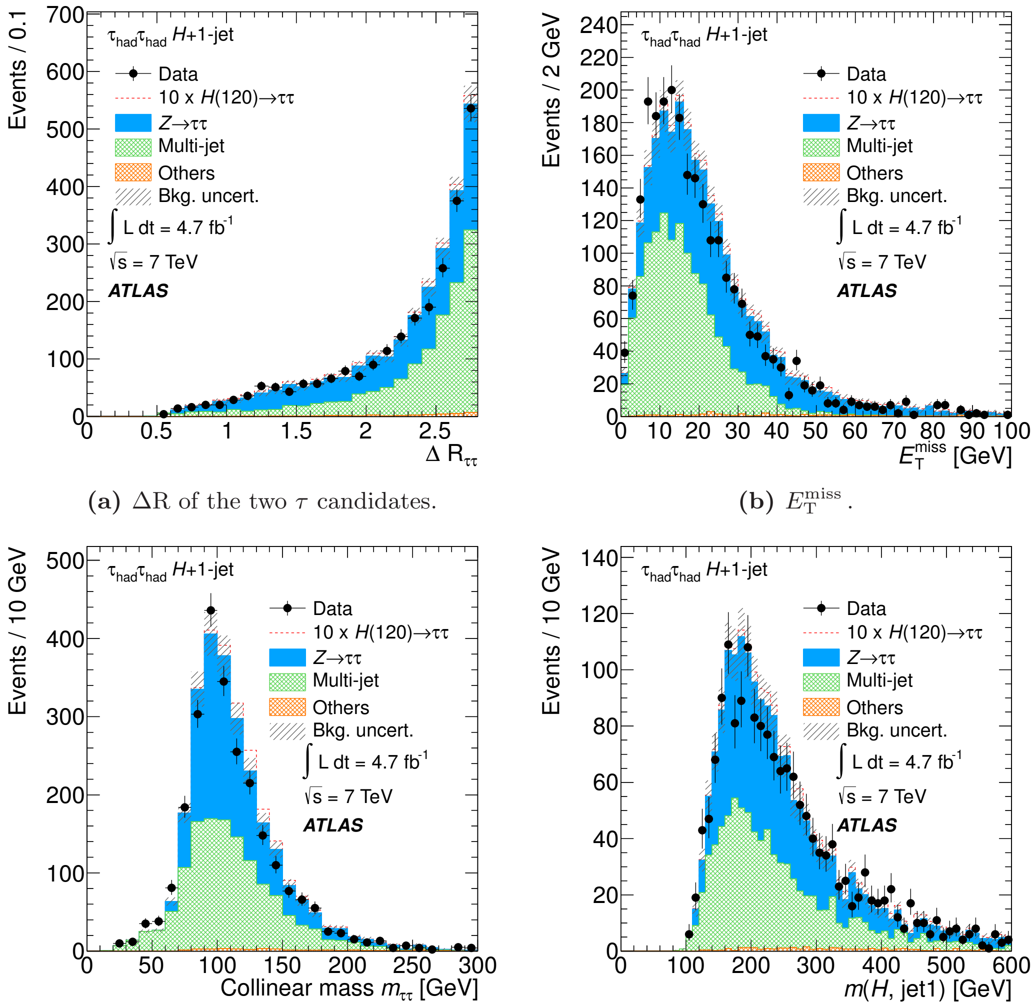

(a) ΔR of the two τ candidates. **(b)** $E_{\mathrm{T}}^{\mathrm{miss}}$.

(c) Collinear mass. **(d)** Invariant mass $m(H, \mathrm{jet1})$.

Figure 6. (a) ΔR of the two τ candidates, (b) missing transverse momentum, (c) collinear mass and (d) invariant mass of the reconstructed Higgs boson and the leading jet in the $H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$ control region. Expectations from the Higgs boson signal ($m_H = 120$ GeV) and from backgrounds are given. The error band indicates the total background uncertainty. For illustration only, the signal contributions, which are expected to be small in this control region, have been scaled by factors given in the legends.

Table 3 presents the event yields after the full event selection, where the yields are normalised to 4.7 fb^{-1}. The collinear mass distribution after full selection is presented in figure 7.

7 Systematic uncertainties

Systematic uncertainties on the normalisation and shape of the signal and background mass distributions are taken into account. These are treated either as fully correlated or uncorrelated across categories. In the case of partial correlations, the source is separated

	$H \to \tau_{\rm had}\tau_{\rm had}$
	H +1-jet
$gg \to H$ signal	3.1 $\pm$ 0.2 $\pm$ 0.6
VBF H signal	1.51 $\pm$ 0.05 $\pm$ 0.18
VH signal	0.61 $\pm$ 0.04 $\pm$ 0.06
$Z/\gamma^* \to \tau^+\tau^-$	287 $\pm$ 23 $\pm$ 34
W+jets / Z+jets	6.1 $\pm$ 1.3 $\pm$ 1.4
$t\bar{t}$+single top	1.9 $\pm$ 0.3 $\pm$ 0.4
$WW/WZ/ZZ$	2.1 $\pm$ 0.4 $\pm$ 0.4
Multi-jet	54 $\pm$ 21 $\pm$ 12
Total background	348 $\pm$ 31 $\pm$ 36
Observed data	317

Table 3. Number of events after the $H \to \tau_{\rm had}\tau_{\rm had}$ selection in data and predicted number of background events, for an integrated luminosity of 4.7 fb^{-1}. Predictions for the Higgs boson signal (m_H = 120 GeV) are also given. Statistical errors and systematic uncertainties are quoted, in that order.

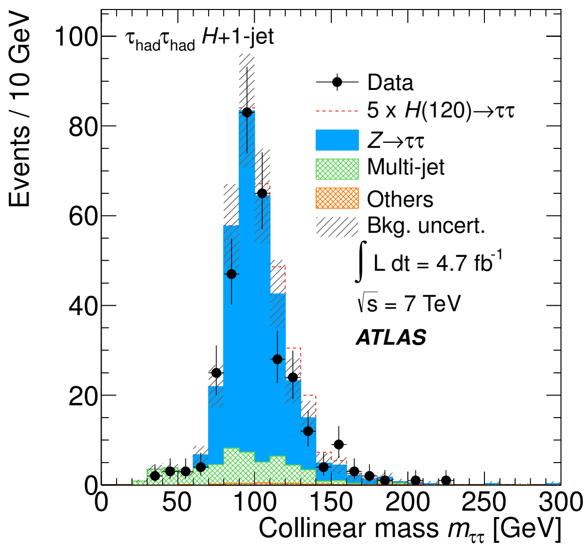

Figure 7. Reconstructed $m_{\tau\tau}$ of the selected events in the $H \to \tau_{\rm had}\tau_{\rm had}$ channel. Expectations from the Higgs boson signal (m_H = 120 GeV) and from backgrounds are given. Results are shown after all selection criteria (see text). For illustration only, the signal contribution has been scaled by a factor given in the legend.

into correlated and uncorrelated components. The dominant correlated systematic uncertainties are those on the measurement of the integrated luminosity and on the theoretical predictions of the signal production cross sections and decay branching ratios, as well as those related to detector response that impact the analyses through the reconstruction of electrons, muons, hadronic τ decays, jets, $E_{\mathrm{T}}^{\mathrm{miss}}$ and b-tagging.

Theoretical uncertainties. The Higgs boson cross section, branching ratios and their uncertainties are compiled in refs. [66, 67]. The QCD scale uncertainties on the signal cross sections depend on m_H and are of the order of 1% for the VBF and VH production modes and in the range of 8–25% for $gg \to H$ depending on jet multiplicity [68, 69]. An uncertainty of 4–5% is assumed for the inclusive cross section of the single vector boson and di-boson production mechanisms and a relative uncertainty of 24% is added in quadrature per additional jet [39, 70]. For both $t\bar{t}$ production and single top-quark production, the QCD scale uncertainties are in the range of 3–6% [71–73]. The uncertainties related to the PDF amount to 8% for the predominantly gluon-initiated processes, $gg \to H$ and $t\bar{t}$, and 4% for the predominantly quark-initiated processes, VBF, VH, single vector boson and di-boson production [74–77]. The systematic uncertainty arising from the choice of different sets of PDF is included. In addition to the theoretical errors considered in ref. [67], other effects are taken into account. Uncertainties related to hadronisation effects are estimated by replacing PYTHIA with HERWIG. Effects due to initial and final state radiation are assessed with PYTHIA samples where the gluon emission is changed according to ref. [78]. The effect of a different choice of parton shower and underlying event parametrisation yields a total uncertainty of about 10% on the acceptance of the Higgs boson produced via the VBF mechanism in the H+2jet VBF channel.

Detector-related uncertainties. The uncertainty on the integrated luminosity is considered as fully correlated across all analysis categories and amounts to 3.9% [79, 80]. The effect of pileup on the signal and background expectations is modelled in the Monte Carlo simulations and the corresponding uncertainty is taken into account.

Appropriate scale factors for the trigger efficiencies of electron, muon and hadronic τ triggers are obtained from data and applied to the Monte Carlo simulations. The associated systematic uncertainties are typically 1–2%. Differences between data and Monte Carlo simulations in the reconstruction and identification efficiencies of τ leptons, electrons and muons are taken into account, as well as the differences in the momentum scales and resolutions.

The systematic uncertainties on the hadronic τ decay identification efficiency are estimated from data samples enriched in $W \to \tau\nu$ and $Z/\gamma^* \to \tau\tau$ events and they are less than 4%. The energy scale uncertainties on the hadronic τ and jets are evaluated based on the single hadron response in the calorimeters [53]. In addition, the τ_{had} energy scale is validated in data samples enriched in $Z/\gamma^* \to \tau\tau$ events. The systematic uncertainties related to the τ and jet energy scale, resolution and b-veto are modelled as functions of η and p_{T}. The jet and τ energy scale and resolution uncertainties are treated as correlated and propagated to the $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation. Uncertainties associated with the remaining pileup noise and cluster activity in the calorimeters are also considered as independent $E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainties.

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The detector-related uncertainties depend on the event topology and are typically small compared to the theoretical uncertainties. The main exceptions are the jet energy scale uncertainty, which is in the range 2.5–12%, and the τ energy scale uncertainty, which is in the range 2–5%.

Background modelling uncertainties. The modelling of the $Z/\gamma^* \to \tau\tau$ background is performed with the data, as described in section 2. Corresponding uncertainties are obtained by propagating variations of the $Z/\gamma^* \to \mu\mu$ event selection and the muon energy subtraction procedure through the τ-embedding procedure. Backgrounds with misreconstructed leptons and τ_{had} candidates are estimated with data and the uncertainty in the estimation lies in the range of 6–40%. The uncertainty takes into account the dependence on the number of jets. The treatment of the other background processes varies across channels and the uncertainties related to the modelling are taken into account as described in section 6.

8 Statistical analysis

The statistical analysis of the data employs a binned likelihood function constructed as the product of the likelihood terms for each category. A total of twelve categories are considered from the $H \to \tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$, $H \to \tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ and $H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channels. The likelihood in each category is a product over bins in the distributions of the MMC mass, collinear mass or effective mass shown in figures 3, 5 and 7.

The expected signal and background, as well as the observed number of events, in each bin of the mass distributions enter in the definition of the likelihood function $\mathcal{L}(\mu, \boldsymbol{\theta})$. A "signal strength" parameter (μ) multiplies the expected signal in each bin. The signal strength is a free parameter in the fit procedure. The value $\mu = 0$ ($\mu = 1$) corresponds to the absence (presence) of a Higgs boson signal with the SM production cross-section. Signal and background predictions (s and b) depend on systematic uncertainties that are parametrised by nuisance parameters $\boldsymbol{\theta}$, which in turn are constrained using Gaussian functions. The correlation of the systematic uncertainties across categories are taken into account:

$$\mathcal{L}(\mu, \theta) = \prod_{\mathrm{bin}\, j} \mathrm{Poisson}(N_j | \mu(s_j) + b_j) \prod_{\theta} \mathrm{Gaussian}(t | \theta, 1), \tag{8.1}$$

where t represents the auxiliary measurements, such as control regions and dedicated calibration measurements. The expected signal and background event counts in each bin are functions of $\boldsymbol{\theta}$. The parametrisation is chosen such that the rates in each channel are log-normally distributed for a normally distributed $\boldsymbol{\theta}$.

The test statistic q_μ is defined as:

$$q_\mu = -2 \ln \left(\mathcal{L}(\mu, \hat{\boldsymbol{\theta}}_\mu) / \mathcal{L}(\hat{\mu}, \hat{\boldsymbol{\theta}}) \right), \tag{8.2}$$

where $\hat{\mu}$ and $\hat{\boldsymbol{\theta}}$ refer to the global maximum of the likelihood (with the constraint $0 \le \hat{\mu} \le \mu$) and $\hat{\boldsymbol{\theta}}_\mu$ corresponds to the conditional maximum likelihood of $\boldsymbol{\theta}$ for a given μ. This test statistic is used to compute exclusion limits following the modified frequentist method known as CL_s [81]. The asymptotic approximation [82] is used to evaluate the Gaussian probability density functions rather than performing pseudo-experiments and the procedure has been validated using ensemble tests.

The profile likelihood formalism used in this statistical analysis incorporates the information on the observed and expected number of events, nuisance parameters, probability density functions and parameters of interest. The statistical significance of an excess is evaluated in terms of the same profile likelihood test statistic. The expected sensitivity and the $\pm 1, 2\,\sigma$ bands are obtained for the background expectation in the absence of a Standard Model Higgs boson signal. The consistency with the background-only hypothesis is quantified using the p-value, the probability that the test statistic of a background-only experiment fluctuates to at least the observed one.

9 Results

No significant excess is observed in the data compared to the SM expectation in any of the channels studied here. Exclusion limits at the 95% confidence level, normalised to the Standard Model cross section times the branching ratio of $H \to \tau^+\tau^-$ (σ_{SM}), are set as a function of the Higgs boson mass. Figure 8 shows expected and observed limits for the individual channels and for the combined result. The combined expected limits vary between 3.4 and 8.2 times the predicted Standard Model cross section times branching ratio for the mass range 100–150 GeV. The most sensitive categories are the H+1-jet category in the $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel, the H+2-jet VBF category in the $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel and the H+2-jet VBF category in the $\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ channel. The observed limits are in the range between 2.9 and 11.7 times the predicted Standard Model cross section times branching ratio for the same mass range. The most significant deviation from the background-only hypothesis is observed in the combined limit for $m_H = 150$ GeV with a local p-value of 10%, corresponding to a significance of 1.3 σ.

10 Conclusions

A search for a Higgs boson decaying in the $H \to \tau\tau$ channel has been performed with the ATLAS detector at the Large Hadron Collider. It uses the full 2011 data sample of 4.7 fb^{-1} collected at a centre-of-mass energy of 7 TeV. The $H \to \tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$, $H \to \tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ and $H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$ decays are considered in this search. No significant excess is observed in the mass range of 100–150 GeV. The observed (expected) upper limits on the cross section times the branching ratio of $H \to \tau\tau$ are between 2.9 (3.4) and 11.7 (8.2) times the SM prediction. These limits are similar to results recently reported by the CMS experiment [83].

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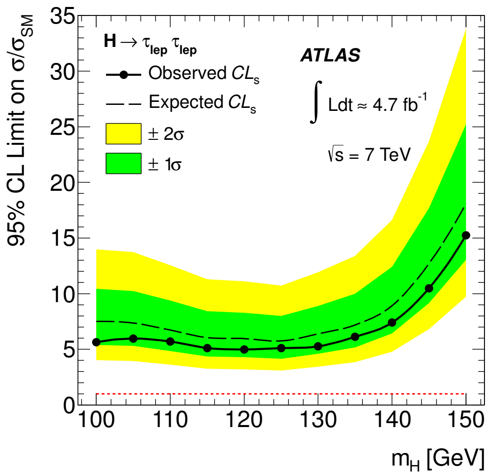
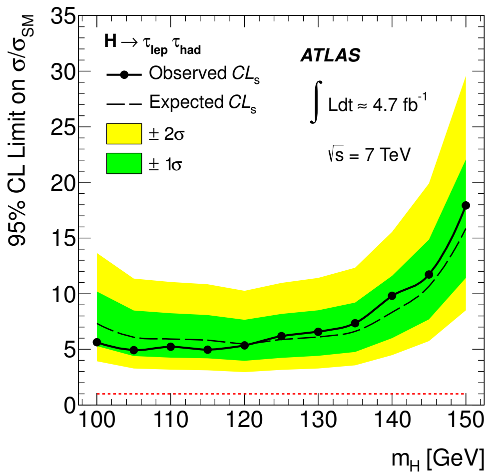
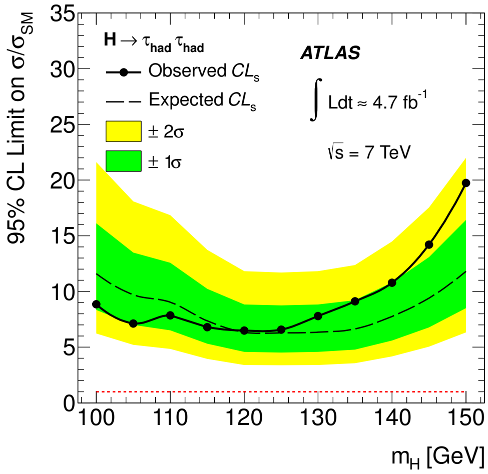


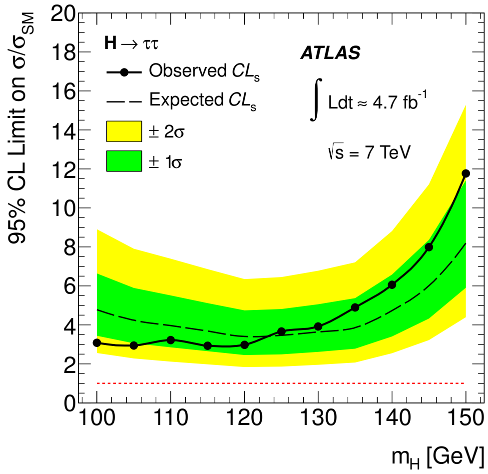
(a) $H \to \tau_{\rm lep}\tau_{\rm lep}$.



(b) $H \to \tau_{\rm lep}\tau_{\rm had}$.



(c) $H \to \tau_{\rm had}\tau_{\rm had}$.



(d) Combined.

Figure 8. Observed (solid) and expected (dashed) 95% confidence level upper limits on the Higgs boson cross section times branching ratio, normalised to the Standard Model expectation, as a function of the Higgs boson mass. Expected limits are given for the scenario with no signal. The bands around the dashed line indicate the expected statistical fluctuations of the limit. Results are given for the $H \to \tau_{\rm lep}\tau_{\rm lep}$, $H \to \tau_{\rm lep}\tau_{\rm had}$, and $H \to \tau_{\rm had}\tau_{\rm had}$ channels independently and for all channels combined.

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