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# Measurement of the $W \to \tau\nu_\tau$ cross section in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS experiment ☆

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ABSTRACT

The cross section for the production of $W$ bosons with subsequent decay $W \to \tau\nu_\tau$ is measured with the ATLAS detector at the LHC. The analysis is based on a data sample that was recorded in 2010 at a proton–proton center-of-mass energy of $\sqrt{s} = 7$ TeV and corresponds to an integrated luminosity of 34 pb$^{-1}$. The cross section is measured in a region of high detector acceptance and then extrapolated to the full phase space. The product of the total $W$ production cross section and the $W \to \tau\nu_\tau$ branching ratio is measured to be $\sigma^{\text{tot}}_{W\to\tau\nu_\tau} = 11.1 \pm 0.3\ (\text{stat}) \pm 1.7\ (\text{syst}) \pm 0.4\ (\text{lumi})$ nb.



## 1. Introduction

The study of processes with $\tau$ leptons in the final state is an important part of the ATLAS physics program, for example in view of searches for the Higgs boson or supersymmetry [1–3]. Decays of Standard Model particles to $\tau$ leptons, in particular $Z \to \tau\tau$ and $W \to \tau\nu_\tau$, are important background processes in such searches. Studies of the $W \to \tau\nu_\tau$ decay complement the measurement of $W$ production in the muon and electron decay modes [4,5]. In addition, $W \to \tau\nu_\tau$ decays can be used to validate the reconstruction and identification techniques for $\tau$ leptons and the measurement of the missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$), which are both fundamental signatures in a wide spectrum of measurements at the LHC.

At next-to-next-to-leading order (NNLO), the $W \to \tau\nu_\tau$ signal is predicted to be produced at $\sqrt{s} = 7$ TeV with a cross section times branching ratio of $\sigma \times \text{BR} = 10.46 \pm 0.52$ nb [6–8]. Since purely leptonic $\tau$ decays cannot be easily distinguished from electrons and muons from $W \to e\nu_e$ or $W \to \mu\nu_\mu$ decays, the analysis presented in this Letter uses only hadronically decaying $\tau$ leptons ($\tau_{\mathrm{h}}$). Events from $W \to \tau\nu_\tau$ production contain predominantly low-$p_{\mathrm{T}}$ $W$ bosons decaying into $\tau$ leptons with typical visible transverse momenta between 10 and 40 GeV. In addition, the distribution of the missing transverse energy, associated with the neutrinos from the $W$ and $\tau_{\mathrm{h}}$ decays, has a maximum around 20 GeV and a significant tail up to about 80 GeV.

Previous measurements at hadron colliders of $W$ boson production with the subsequent decay $W \to \tau\nu_\tau$ based on $p\bar{p}$ collisions were reported by the UA1 Collaboration [9] at center-of-mass energies of $\sqrt{s} = 546$ GeV and $\sqrt{s} = 630$ GeV and by the CDF and D0 Collaborations [10,11] at a center-of-mass energy of $\sqrt{s} = 1.8$ TeV.

In this Letter, we describe the measurement of this process with $\sqrt{s} = 7$ TeV $pp$ collision data, which were recorded with the ATLAS experiment at the LHC.

## 2. The ATLAS detector

The ATLAS detector is described in Ref. [12]. The cylindrical coordinate system is defined with polar angles $\theta$ relative to the beamline and azimuthal angles $\phi$ in the plane transverse to the beam. Pseudorapidities $\eta$ are defined as $\eta = -\ln\tan\frac{\theta}{2}$. Transverse momenta, $p_{\mathrm{T}}$, are defined as the component of momentum perpendicular to the beamline. Distances are measured in the $\eta$–$\phi$ plane as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.

Measurements of charged-particle trajectories and momenta are performed with silicon detectors in the pseudorapidity range $|\eta| < 2.5$, and also by a straw-tube tracking chamber in the range $|\eta| < 2.0$. Together, these systems form the inner tracking detector, which is contained in a 2 T magnetic field produced by a superconducting solenoid. These tracking detectors are surrounded by a finely segmented calorimeter system which provides three-dimensional reconstruction of particle showers up to $|\eta| < 4.9$. The electromagnetic calorimeter uses liquid argon as the active material and comprises separate barrel ($|\eta| < 1.5$), end-cap ($1.4 < |\eta| < 3.2$) and forward ($3.2 < |\eta| < 4.9$) components. The hadron


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calorimeter is based on scintillating tiles in the central region ($|\eta| < 1.7$). It is extended up to $|\eta| = 4.9$ by end-caps and forward calorimeters which use liquid argon. The muon spectrometer measures the deflection of muon tracks in the field of three large superconducting toroidal magnets. It is instrumented with trigger and high-precision tracking chambers.

The trigger system consists of three levels. The first level is implemented as a hardware trigger, while the decision on the following levels is based on software event processing similar to the offline reconstruction.

## 3. Data samples

The data used in this measurement were recorded in proton–proton collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV during the 2010 LHC run. The integrated luminosity of the data sample, considering only data-taking periods where all relevant detector subsystems were fully operational, is 34 $\text{pb}^{-1}$ [13,14]. The data were collected using triggers combining the two main signatures of $W \to \tau_h \nu_\tau$ decays, namely the presence of a hadronically decaying $\tau$ lepton and missing transverse energy.

Processes producing $W$ or $Z$ bosons that subsequently decay into electrons or muons constitute important backgrounds to this measurement if the lepton from the decay or an accompanying jet is misidentified as a hadronically decaying $\tau$ lepton. Here, the missing transverse energy signature arises from a $W$ decay neutrino or the misreconstruction of jets or of other objects in the event. Also, $W \to \tau\nu_\tau$ decays with the $\tau$ decaying leptonically are considered as a background. Incompletely reconstructed $Z \to \tau\tau$ and $t\bar{t}$ decays can also enter the signal sample. The number of background events from these electroweak processes is referred to as $N_{\text{EW}}$ in the following.

The production of $W$ and $Z$ bosons in association with jets is simulated with the PYTHIA [15] generator with the modified LO parton distribution function (PDF) MRSTLO* [16] and normalized to the NNLO cross section; $t\bar{t}$ processes are generated with MC@NLO [17], where parton showers and hadronization are simulated with HERWIG [18] and the underlying event with JIMMY [19]. The TAUOLA [20] and PHOTOS [21] programs are used to model the decay of $\tau$ leptons and the QED radiation of photons, respectively.

All simulated samples include multiple proton–proton interactions (pile-up) produced with PYTHIA using the ATLAS MC10 tune [22]. Those samples are passed through a full detector simulation based on GEANT4 [23,24]. The simulated events are reweighted so that the distribution of the number of reconstructed primary vertices per bunch crossing matches the data.

Due to their large production cross sections, QCD processes provide a significant background if quark/gluon jets (QCD jets) are misidentified as hadronic $\tau$ decays and a significant amount of $E_{\text{T}}^{\text{miss}}$ is measured, mainly due to incomplete reconstruction. The number of QCD background events $N_{\text{QCD}}$ is estimated directly from data.

## 4. Object reconstruction

Electron candidates, which together with muons are relevant for the electroweak background, are reconstructed from a cluster in the electromagnetic calorimeter matched to a track in the inner tracking detector. The cluster must have a shower profile consistent with an electromagnetic shower [25]. Muon candidates are reconstructed by combining tracks in the muon spectrometer with tracks in the inner tracking detector [26].

Jets are reconstructed with the anti-$k_t$ algorithm [27] with a radius parameter $R = 0.4$. The jet energies are calibrated [28] using a $p_{\text{T}}$- and $\eta$-dependent calibration scheme, corrected for losses in dead material and outside the jet cone [29]. All jets considered in this analysis are required to have a transverse momentum above 20 GeV and a pseudorapidity in the range $|\eta| < 4.5$.

Reconstructed jets within $|\eta| < 2.5$ provide the starting point (seed) for the reconstruction of hadronic $\tau$ decays. The direction of a $\tau_h$ candidate is taken directly from the corresponding seed jet. The energy is calibrated by applying a dedicated correction extracted from Monte Carlo to the sum of energies of the cells that form the clusters of the seed jet [30]. Therefore, the energy of the $\tau_h$ refers to the visible decay products. The transverse momentum is calculated as $p_{\text{T}} = E \sin\theta$, i.e. $\tau_h$ candidates are treated as massless. Good-quality tracks are associated with a $\tau_h$ candidate if they are found within $\Delta R < 0.2$ around the seed jet axis. At least one track must be associated to the candidate.

The $\tau_h$ identification [30] is based on eight observables: The invariant mass of the $\tau$ decay products is calculated separately using the associated tracks and the associated clusters. The fact that the $\tau$ decay products are typically more collimated than QCD jets is quantified by calculating the transverse momentum-weighted radius from tracks and the energy-weighted radius from electromagnetic energy information. The fraction of transverse energy within $\Delta R < 0.1$ of the $\tau_h$ seed direction is used as well. Further discrimination is provided by the fraction of the transverse $\tau_h$ momentum carried by the highest-$p_{\text{T}}$ track and the fraction of transverse energy deposited in the electromagnetic calorimeter, for which higher values are expected in case of hadronic $\tau$ decays compared to QCD jets. For $\tau_h$ candidates with more than one associated track, the $\tau$ lifetime is also exploited by measuring the decay length significance of the associated secondary vertex in the transverse plane. The single most discriminating of these quantities is the energy-weighted radius

$$R_{\text{EM}} = \frac{\sum_i^{\Delta R_i < 0.4} E_{\text{T},i}^{\text{EM}} \Delta R_i}{\sum_i^{\Delta R_i < 0.4} E_{\text{T},i}^{\text{EM}}}, \tag{1}$$

where $i$ iterates over cells in the first three layers of the electromagnetic calorimeter associated with the $\tau_h$ candidate, $\Delta R_i$ is defined relative to the $\tau_h$ seed axis, and $E_{\text{T},i}^{\text{EM}}$ is the cell transverse energy.

These eight variables are combined in a boosted decision tree discriminator (BDT) [31], which provides an output value between 0 (background-like) and 1 (signal-like) with a continuous gradient of signal and background efficiency. This discriminator was optimized using a combination of $W \to \tau_h \nu_\tau$ and $Z \to \tau\tau$ Monte Carlo samples for the signal. The background was modeled from dijet events selected from data. For $\tau_h$ transverse momenta ($p_{\text{T}}^{\tau_h}$) above 20 GeV, the efficiency of the $\tau_h$ identification at the tighter working point of the BDT identification considered for this measurement is about 30% with a jet rejection factor of 100 for $\tau_h$ candidates with one track, while for candidates with three tracks it is about 35% with a rejection factor of 300 [30]. Additional requirements on the calorimeter and tracking properties of $\tau_h$ candidates are used to discriminate against electrons and muons.

The missing transverse energy in the event, $E_{\text{T}}^{\text{miss}}$, is reconstructed as $\sqrt{(E_{\text{x}}^{\text{miss}})^2 + (E_{\text{y}}^{\text{miss}})^2}$, where $(E_{\text{x}}^{\text{miss}}, E_{\text{y}}^{\text{miss}})$ is the vector sum of all calorimeter energy clusters in the region $|\eta| < 4.5$, corrected for identified muons [32]. With good approximation, the resolution of $E_{\text{T}}^{\text{miss}}$ components is proportional to $a \times \sqrt{\sum E_{\text{T}}}$, where the scaling factor $a$ depends on both the detector and reconstruction performance and $\sum E_{\text{T}}$ is calculated from all calorimeter energy clusters. The factor $a$ is about $0.5\sqrt{\text{GeV}}$ for minimum bias events [33].

In order to reject events with large reconstructed $E_T^{miss}$ due to fluctuations in the energy measurement, we define the significance of $E_T^{miss}$ as

$$S_{E_T^{miss}} = \frac{E_T^{miss}[\mathrm{GeV}]}{0.5\sqrt{\mathrm{GeV}}\sqrt{(\sum E_T[\mathrm{GeV}])}}. \tag{2}$$

$S_{E_T^{miss}}$ is found to provide better discrimination between the signal and the background from QCD jets than a simple $E_T^{miss}$ requirement.

## 5. Event selection

Events are selected using triggers based on the presence of a $\tau_h$ jet and $E_T^{miss}$. In the earlier part of the 2010 data taking, corresponding to an integrated luminosity of 11 $\mathrm{pb}^{-1}$, a loosely identified $\tau_h$ candidate with $p_T^{\tau_h} > 12$ GeV (as reconstructed at the trigger level) in combination with $E_T^{miss} > 20$ GeV was required. In the second part of the period (24 $\mathrm{pb}^{-1}$), a tighter $\tau_h$ identification and higher thresholds of 16 GeV and 22 GeV had to be used for $p_T^{\tau_h}$ and $E_T^{miss}$, respectively, due to the increasing luminosity. The signal efficiencies of these two triggers with respect to the offline selection are estimated from the simulation to be $(81.3 \pm 0.8)\%$ and $(62.7 \pm 0.7)\%$, respectively.

Events satisfying the trigger selection are required to have at least one reconstructed vertex that is formed by three or more tracks with $p_T > 150$ MeV. Further selection requirements based on calorimeter information are applied to reject non-collision events and events containing jets that were incompletely reconstructed or significantly affected by electronic noise in the calorimeters.

The calorimeter has a lower resolution for jets in the barrel-endcap transition regions. In order to ensure a uniform $E_T^{miss}$ resolution, events are rejected if a jet or a $\tau_h$ candidate with $1.3 < |\eta| < 1.7$ is found. In events where the $E_T^{miss}$ is found to be collinear to one of the jets, the reconstructed $E_T^{miss}$ is likely to originate from an incomplete reconstruction of this jet. Therefore, a minimum separation $|\Delta\phi(\mathrm{jet}, E_T^{miss})| > 0.5$ rad is required.

In order to suppress backgrounds from other leptonic $W$ and $Z$ decays, events containing identified electrons or muons with $p_T > 15$ GeV are rejected. The highest-$p_T$ identified $\tau_h$ candidate in the event is considered for further analysis and required to be in the pseudorapidity range $|\eta| < 2.5$ and to have $20 < p_T^{\tau_h} < 60$ GeV. A minimum $E_T^{miss}$ of 30 GeV is required and events are rejected if $S_{E_T^{miss}} < 6$.

## 6. Background estimation

The number of expected events from signal and electroweak background processes is obtained from simulation. This is justified by the good agreement between data and simulation observed in the ATLAS $W$ cross section measurements [4,5] through decays into electrons or muons. It is further validated using a high-purity data sample of $W \to \mu\nu_\mu$ events, in which the muon is removed and replaced by a simulated $\tau_h$ lepton. Thus, only the $\tau$ decay and the corresponding detector response are taken from simulation while the underlying $W$ kinematics and all the other properties of the event are obtained from the $W \to \mu\nu_\mu$ events selected in data. Fig. 1 compares the distribution of $S_{E_T^{miss}}$ for the $\tau_h$-embedded data sample with simulated $W \to \tau_h\nu_\tau$ events. A good agreement is observed within the statistical uncertainties, which adds further confidence in the electroweak background event model provided by the simulated event samples used in this analysis.

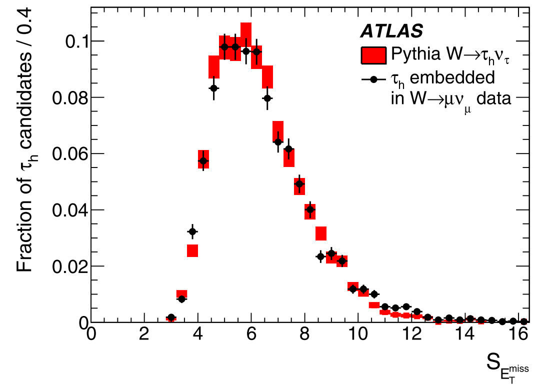


**Fig. 1.** Distribution of $S_{E_T^{miss}}$ for the $\tau_h$-embedded $W \to \mu\nu_\mu$ data sample (points) and simulated $W \to \tau_h\nu_\tau$ events (histogram), including statistical uncertainties.

The background contribution from QCD jet production, for which the cross section is large and the selection efficiency is low, cannot be reliably modeled using simulated events alone and is thus estimated from data. In addition to the signal-dominated data set defined by the selection described in Section 5, three background control regions are defined by inverting the requirements on the $S_{E_T^{miss}}$ and/or the $\tau_h$ identification (ID), resulting in the following four samples:

- Region A: $S_{E_T^{miss}} > 6.0$ and $\tau_h$ candidates satisfying the signal $\tau_h$ ID requirements described in Section 4;
- Region B: $S_{E_T^{miss}} < 4.5$ and $\tau_h$ candidates satisfying the signal-region $\tau_h$ ID requirements;
- Region C: $S_{E_T^{miss}} > 6.0$ and $\tau_h$ candidates satisfying a looser $\tau_h$-ID but failing the signal-region $\tau_h$ ID requirements;
- Region D: $S_{E_T^{miss}} < 4.5$ and $\tau_h$ candidates satisfying a looser $\tau_h$-ID but failing the signal-region $\tau_h$ ID requirements.

Here, the looser $\tau_h$-ID region is defined by selecting $\tau_h$ candidates with a lower value of the BDT output.

After ensuring that the shape of the $S_{E_T^{miss}}$ distribution for the QCD background is independent of the $\tau_h$-ID requirement and assuming that the signal and electroweak background contributions in the three control regions are negligible, an estimate for the number of QCD background events in the signal region A is provided by

$$N_{QCD}^{A} = N^{B} N^{C} / N^{D}, \tag{3}$$

where $N^i$ represents the number of observed events in region $i$.

In order to take into account the residual signal and EW background contamination in the control regions $i = \mathrm{B, C, D}$, the number of selected events, $N^i$, needs to be replaced in Eq. (3) by $N^i - c_i(N^A - N_{QCD}^A)$, where

$$c_i = \frac{N_{sig}^{i} + N_{EW}^{i}}{N_{sig}^{A} + N_{EW}^{A}} \tag{4}$$

is the ratio of simulated signal and EW background events in the control region $i$ and the signal region. Therefore Eq. (3) becomes

$$N_{QCD}^{A} = \frac{[N^{B} - c_{B}(N^{A} - N_{QCD}^{A})][N^{C} - c_{C}(N^{A} - N_{QCD}^{A})]}{N^{D} - c_{D}(N^{A} - N_{QCD}^{A})}. \tag{5}$$

The statistical error on $N_{QCD}^{A}$ includes both the uncertainty on the calculation of the $c_i$ coefficients, due to the Monte Carlo statis-

**Table 1**
Estimated sample compositions and $c_i$ factors (as defined in Eq. (4)) in the signal region A and control regions B, C, and D defined in the text.

| | A | B | C | D |
|---|---|---|---|---|
| $N^i$ (Data) | 2335 | 4796 | 1577 | 27 636 |
| $N^i_{\text{sig}}$ ($W \to \tau_h \nu_\tau$) | $1811 \pm 25$ | $683 \pm 16$ | $269 \pm 8$ | $93 \pm 5$ |
| $N^i_{\text{EW}}$ | $284 \pm 7$ | $118 \pm 4$ | $388 \pm 9$ | $90 \pm 4$ |
| $c_i$ | | $0.38 \pm 0.01$ | $0.31 \pm 0.01$ | $0.087 \pm 0.003$ |
| $N^i_{\text{QCD}}$ | $127 \pm 8$ | $3953 \pm 75$ | $885 \pm 45$ | $27\,444 \pm 166$ |

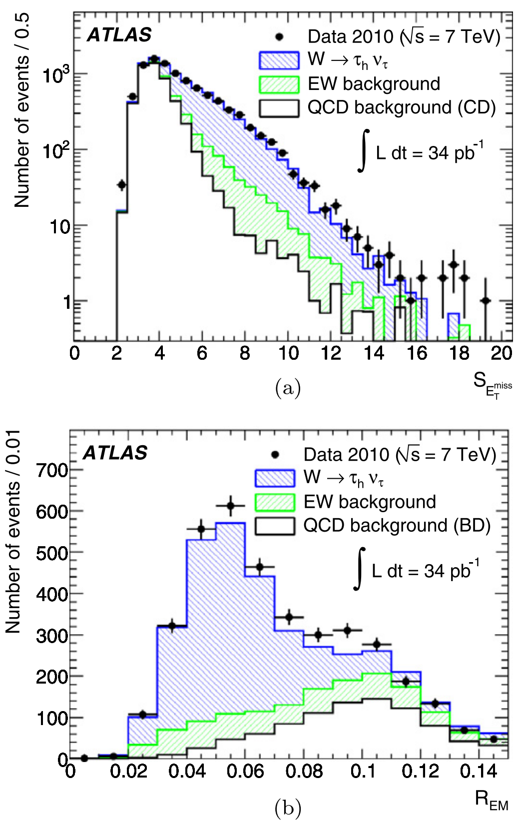


**Fig. 2.** (a) $S_{E_T^{\text{miss}}}$ distribution in the combined region AB, extended over the full $S_{E_T^{\text{miss}}}$ range. The QCD background shape has been extracted from regions CD. Monte Carlo signal and EW background in regions AB are also shown; (b) the $\tau_h$ identification variable $R_{\text{EM}}$ in the combined region AC. The QCD background shape has been extracted from regions BD. Monte Carlo signal and EW background in regions AC are also shown.

tics, and the statistical uncertainty of the data in the four regions. The resulting estimates of the sample compositions are summarized in Table 1.

The quality of the description of the selected data by the background models can be judged from Figs. 2 and 3, where data and the background estimates (EW and QCD) are shown. Fig. 2(a) shows the distribution of $S_{E_T^{\text{miss}}}$ in regions A and B, extended over the full $S_{E_T^{\text{miss}}}$ range, for all events passing the selection criteria except for the $S_{E_T^{\text{miss}}}$ requirement. In Fig. 2(b) the distribution of $R_{\text{EM}}$ is shown. In this case events passing the selection criteria but considering $\tau_h$ candidates identified by the loose and the tight selections in regions A and C are shown. The agreement between data and Monte Carlo expectation confirms the results obtained by the data-driven background estimation. In Fig. 3 the distribution of $E_T^{\text{miss}}$, the $p_T^{\tau_h}$ spectrum, the number of tracks associated to the $\tau_h$ candidate, the distribution of $\Delta\phi(\tau_h, E_T^{\text{miss}})$ and the transverse mass, $m_T = \sqrt{2 \cdot p_T^{\tau_h} \cdot E_T^{\text{miss}} \cdot (1 - \cos\Delta\phi(\tau_h, E_T^{\text{miss}}))}$, in the selected signal region A are shown, illustrating the characteristic properties of $W \to \tau_h \nu_\tau$ decays. In all the distributions reasonable agreement is observed between the data and Monte Carlo prediction.

## 7. Cross section measurement

The fiducial cross section is measured in a phase space region given by the geometrical acceptance of the detector and by the kinematic selection of the analysis (as described in Section 5). This region is defined based on the decay products from a simulated hadronic $\tau$ decay and corresponds to the criteria presented in Table 2.

Here, the visible $\tau$ momentum $p_T^{\tau,\text{vis}}$ and pseudorapidity $\eta^{\tau,\text{vis}}$ are calculated from the sum of the four-vectors of the decay products from the simulated hadronic $\tau$ decay, except for the neutrinos. This momentum also includes photons radiated both from the $\tau$ lepton and from the decay products themselves, considering only photons within $\Delta R < 0.4$ with respect to the $\tau_h$. The minimum $E_T^{\text{miss}}$ requirement translates into a cut on the transverse component of the sum of the simulated neutrino four-vectors $(\sum p^\nu)_T$.

The fiducial cross section, including the branching ratio $\text{BR}(W \to \tau_h \nu_\tau)$, is computed as

$$\sigma^{\text{fid}}_{W \to \tau_h \nu_\tau} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C_W \mathcal{L}}, \tag{6}$$

where $N_{\text{obs}}$ is the number of observed events in data, $N_{\text{bkg}}$ is the number of estimated (QCD and EW) background events (signal region A in Table 1), and $\mathcal{L}$ is the integrated luminosity. $C_W$ is the correction factor that takes into account the efficiency of trigger, $\tau_h$ reconstruction and identification and the efficiency of all selection cuts within the acceptance:

$$C_W = \frac{N_{\text{reco, all cuts}}}{N_{\text{gen, kin/geom}}}, \tag{7}$$

where $N_{\text{reco, all cuts}}$ is the number of fully simulated signal events passing the reconstruction, trigger and the selection cuts of the analysis and $N_{\text{gen, kin/geom}}$ is the number of simulated signal events within the fiducial region defined above.

With the kinematic and geometrical signal acceptance

$$A_W = \frac{N_{\text{gen, kin/geom}}}{N_{\text{gen, all}}}, \tag{8}$$

where $N_{\text{gen, all}}$ is the total number of simulated signal events while $N_{\text{gen, kin/geom}}$ is the denominator of $C_W$, the total cross section

$$\sigma^{\text{tot}}_{W \to \tau_h \nu_\tau} = \sigma^{\text{fid}}_{W \to \tau_h \nu_\tau} / A_W = \frac{N_{\text{obs}} - N_{\text{bkg}}}{A_W C_W \mathcal{L}} \tag{9}$$

can be obtained. $A_W$ and $C_W$ are determined using a PYTHIA Monte Carlo signal sample described in Section 3. The fiducial acceptance is found to be $A_W = 0.0975 \pm 0.0004$ (MC stat) and the correction factor $C_W = 0.0799 \pm 0.0011$ (MC stat).

The measured fiducial cross section of the $W \to \tau_h \nu_\tau$ decay is $\sigma^{\text{fid}}_{W \to \tau_h \nu_\tau} = 0.70 \pm 0.02$ (stat) nb and the total cross section is found to be $\sigma^{\text{tot}}_{W \to \tau_h \nu_\tau} = 7.2 \pm 0.2$ (stat) nb.

Several alternative analyses are performed to confirm these results. For example, the BDT $\tau_h$ ID is replaced by a simpler identification based on cuts on three of the ID variables only [30]. Also, in order to study the influence of pile-up on the result, the signal selection is restricted to events with only one reconstructed primary vertex. In both cases consistent results are found.

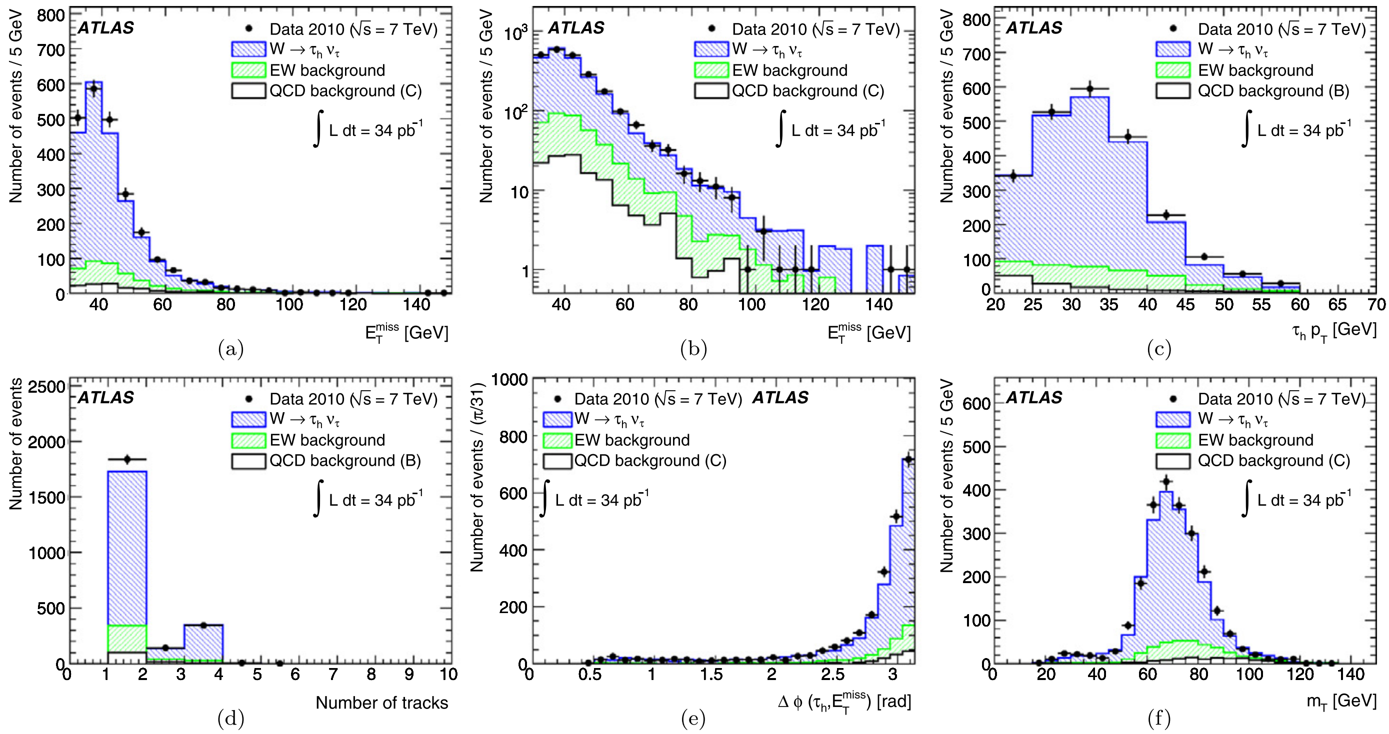


**Fig. 3.** (a) Distribution of missing transverse energy in signal region A on a linear scale. The QCD background shape has been extracted from control region C. (b) Same distribution on a logarithmic scale. (c) Transverse momentum and (d) number of tracks of $\tau_h$ candidates in signal region A. The QCD background shape has been extracted from control region B. (e) Distribution of $\Delta\phi(\tau_h, E_T^{miss})$ and (f) transverse mass $m_T$ in signal region A. The QCD background shape has been extracted from control region C. The expectation from Monte Carlo signal and EW background in region A are also shown.

**Table 2**
Definition of the acceptance region.

| |
|---|
| $20\ \text{GeV} < p_T^{\tau,\text{vis}} < 60\ \text{GeV}$ |
| $\lvert\eta^{\tau,\text{vis}}\rvert < 2.5$, excluding $1.3 < \lvert\eta^{\tau,\text{vis}}\rvert < 1.7$ |
| $(\sum p^{\nu})_T > 30\ \text{GeV}$ |
| $\lvert\Delta\phi(p^{\tau,\text{vis}}, \sum p^{\nu})\rvert > 0.5$ |

## 8. Systematic uncertainties

Table 3 summarizes the systematic uncertainties. The main sources are discussed in the following.

### 8.1. Monte Carlo predictions

The trigger efficiency is determined in Monte Carlo for the combined $E_T^{miss}$ and $\tau_h$ triggers used in the two data periods. The differences between the measured trigger responses of the two trigger components in data and Monte Carlo are used to determine the systematic uncertainty. A pure and unbiased sample enriched with $W \to \tau_h\nu_\tau$ events is obtained in data by applying an independent $\tau_h(E_T^{miss})$ trigger and selected cuts of the event selection like the BDT $\tau_h$ ID. The corresponding $E_T^{miss}(\tau_h)$ trigger part is applied to this sample and the response of this trigger is compared to the response in Monte Carlo. The observed differences are integrated over the offline $p_T^{\tau_h}$ and $E_T^{miss}$ range used for the cross section measurement. The total systematic uncertainty after the combination of the different trigger parts is 6.1%.

The signal and background acceptance depends on the energy scale of the clusters used in the computation of $E_T^{miss}$ and $S_{E_T^{miss}}$ and the energy scale of the calibrated $\tau_h$ candidates. Based on the current knowledge of the calibration the uncertainty due to cluster energy within the detector region $|\eta| < 3.2$ is at most 10% for $p_T$ of 500 MeV and within 3% at high $p_T$ [34]. In the forward region $|\eta| > 3.2$ it is estimated to be 10%. The effect on $E_T^{miss}$ and $S_{E_T^{miss}}$ has been evaluated by scaling all clusters in the event according to these uncertainties and recalculating $E_T^{miss}$ and $\sum E_T$. At the same time, the $\tau_h$ energy scale has been varied according to its uncertainty [30]. This uncertainty depends on the number of tracks associated to the $\tau_h$ candidate, its $p_T$ and the $\eta$ region in which it was reconstructed, and ranges from 2.5% to 10%. In addition, the sensitivity of the signal and background efficiency to the $E_T^{miss}$ resolution has been investigated [33]. Consequently, the yield of signal and EW background varies within 6.7% and 8.7%, respectively.

The identification and reconstruction efficiency of $\tau_h$ candidates was studied with Monte Carlo $W \to \tau_h\nu_\tau$ and $Z \to \tau\tau$ samples and was found to vary with different simulation conditions such as different underlying event models, detector geometry, hadronic shower modeling and noise thresholds for calorimeter cells in the cluster reconstruction. In Ref. [30], these uncertainties are evaluated as a function of $p_T^{\tau_h}$, separately for candidates with one or multiple tracks and low or high multiplicity of primary vertices in the event. The corresponding changes in the signal and EW background efficiencies are found to be 9.6% and 4.1%, respectively.

The probability of a jet or electron to be misidentified as a $\tau_h$ candidate has been evaluated in data and compared with the expectation from Monte Carlo. The rate of jets that are misidentified as $\tau_h$ candidates was calculated using a selection of $W \to \ell\nu_\ell$+jets events (with $\ell = e, \mu$) and measuring the fraction of reconstructed candidates that are found by the $\tau_h$ identification. The difference of this misidentification rate in Monte Carlo compared to that in data is 30% and this was applied as a systematic uncertainty to the fraction of events mimicked by a jet. The overall uncertainty on the EW background is 7.2%. The misidentification probability of

**Table 3**
Summary table for systematic uncertainties. For the systematic uncertainty on the fiducial cross section measurement, correlations between the systematics affecting $C_W$ and $N_{\mathrm{EW}}$ have been taken into account.

| | $\frac{\delta C_W}{C_W}$ | $\frac{\delta N_{\mathrm{EW}}}{N_{\mathrm{EW}}}$ | $\frac{\delta N_{\mathrm{QCD}}}{N_{\mathrm{QCD}}}$ | $\frac{\delta\sigma^{\mathrm{fid}}_{W\to\tau_h\nu_\tau}}{\sigma^{\mathrm{fid}}_{W\to\tau_h\nu_\tau}}$ |
|---|---|---|---|---|
| Trigger efficiency | 6.1% | 6.1% | – | 7.0% |
| Energy scale | 6.7% | 8.7% | – | 8.0% |
| $\tau_h$ ID efficiency | 9.6% | 4.1% | – | 10.3% |
| Jet $\tau_h$ misidentification | – | 7.2% | – | 1.1% |
| Electron $\tau_h$ misidentification | – | 4.5% | – | 0.7% |
| Pile-up reweighting | 1.4% | 1.2% | – | 1.6% |
| Electron reconstruction/identification | – | 1.2% | – | 0.2% |
| Muon reconstruction | – | 0.3% | – | 0.04% |
| Underlying event modeling | 1.3% | 1.1% | – | 1.5% |
| Cross section | – | 4.5% | – | 0.7% |
| QCD estimation: Stability/correlation | – | – | 2.7% | 0.2% |
| QCD estimation: Sig./EW contamination | – | – | 2.1% | 0.1% |
| Monte Carlo statistics | 1.4% | 2.4% | 6.0% | 1.5% |
| Total systematic uncertainty | 13.4% | 15.2% | 6.9% | 15.1% |

electrons as $\tau_h$ candidates has been determined with a "tag-and-probe" method using $Z \to ee$ events where the $\tau_h$ identification and $\tau_h$ electron veto is applied to one of the electrons. The difference between the misidentification probability in data and Monte Carlo as a function of $\eta$ has been applied as a systematic uncertainty to $\tau_h$ candidates mimicked by an electron. It amounts to 4.5% for the total EW background.

Other sources of systematic uncertainty have been evaluated and were found to have only small effects on the resulting cross section measurement, for example the procedure to include pile-up effects, the uncertainty on the lepton selection efficiency entering via the veto of electrons and muons and the influence of the underlying event modeling on $E_T^{\mathrm{miss}}$ quantities. The uncertainties on the cross sections used for the EW background are taken from ATLAS measurements, when available, or theoretical NNLO calculations, and lie between 3 and 9.7% [8,35,6,7]. The uncertainty on the integrated luminosity is 3.4% [13,14].

*8.2. QCD background estimation*

Two different sources of systematic uncertainty arising from the method of estimating the QCD background events from data have been studied. The stability of the method and the small correlation of the two variables ($\tau_h$ ID and $S_{E_T^{\mathrm{miss}}}$) used to define the control regions have been tested by varying the $S_{E_T^{\mathrm{miss}}}$ threshold. The systematic uncertainty due to the correction for signal and EW background contamination in the control regions was obtained by varying the fraction of these events in the regions within the combined systematic and statistical uncertainties on the Monte Carlo predictions discussed above. The total uncertainty on the QCD background estimation is 3.4%.

*8.3. Acceptance*

The theoretical uncertainty on the geometric and kinematic acceptance factor $A_W$ is dominated by the limited knowledge of the proton PDFs and the modeling of $W$ boson production at the LHC.

The uncertainty resulting from the choice of the PDF set is evaluated by comparing the acceptance obtained with different PDF sets (the default MRST LO*, CTEQ6.6 and HERAPDF 1.0 [36]) and within one PDF set by re-weighting the default sample to the different error eigenvectors available for the CTEQ6.6 NLO PDF [37].

**Table 4**
Resulting numbers for the cross section calculation. The errors include statistical and systematic uncertainties here.

| | |
|---|---|
| $N_{\mathrm{obs}}$ | 2335 |
| $N_{\mathrm{QCD}}$ | $127 \pm 9$ |
| $N_{\mathrm{EW}}$ | $284 \pm 43$ |
| $A_W$ | $0.0975 \pm 0.0019$ |
| $C_W$ | $0.0799 \pm 0.0107$ |

The uncertainty is 1.6 % and 1.0%, respectively, which combines to 1.9%.

The uncertainty on the modeling of $W$ production was evaluated by comparing the default sample acceptance to that obtained from an MC@NLO sample where the parton shower is modeled by HERWIG. The difference in acceptance is found to be smaller than 0.5%.

## 9. Results

The results of the analysis relevant to the cross section measurement are summarized in Table 4. Within the acceptance region defined in Table 2 they translate into a fiducial cross section $\sigma^{\mathrm{fid}}_{W\to\tau_h\nu_\tau}$ of

$$0.70 \pm 0.02\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst}) \pm 0.02\ (\mathrm{lumi})\ \mathrm{nb}$$

and a total cross section $\sigma^{\mathrm{tot}}_{W\to\tau_h\nu_\tau}$ of

$$7.2 \pm 0.2\ (\mathrm{stat}) \pm 1.1\ (\mathrm{syst}) \pm 0.2\ (\mathrm{lumi})\ \mathrm{nb}.$$

After correcting the cross section for the hadronic $\tau$ decay branching ratio $\mathrm{BR}(\tau \to h\nu_\tau) = 0.6479 \pm 0.0007$ [38] this yields the following inclusive cross section $\sigma^{\mathrm{tot}}_{W\to\tau\nu_\tau}$:

$$11.1 \pm 0.3\ (\mathrm{stat}) \pm 1.7\ (\mathrm{syst}) \pm 0.4\ (\mathrm{lumi})\ \mathrm{nb}.$$

The measured cross section is in good agreement with the theoretical NNLO cross section $10.46 \pm 0.52$ nb [6–8] and the ATLAS measurements of the $W \to e\nu_e$ and $W \to \mu\nu_\mu$ cross sections [4,5]. The comparison of the cross section measurements for the different lepton final states and the theoretical expectation is shown in Fig. 4. This is the first $W \to \tau\nu_\tau$ cross section measurement performed at the LHC.

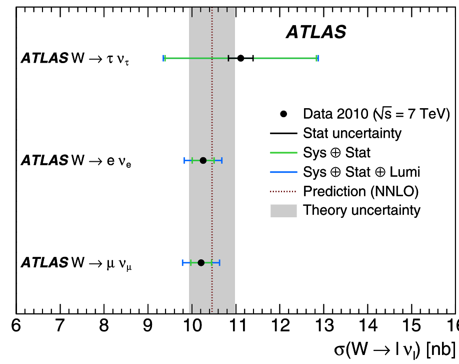


**Fig. 4.** Cross sections for the different $W \to \ell\nu_\ell$ channels measured in ATLAS with 2010 data (points). Systematic, luminosity and statistical uncertainties are added in quadrature. The theoretical NNLO expectation is also shown (dashed line), together with its uncertainty (filled area).

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