A search for high-mass resonances decaying $\tau^+\tau^-$ in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector


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A search for high-mass resonances decaying to $\tau^+\tau^-$ in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

ATLAS Collaboration

1. Introduction

Many extensions of the Standard Model (SM), motivated by grand unification, predict additional heavy gauge bosons [1–6]. As lepton universality is not necessarily a requirement for these new gauge bosons, it is essential to search in all decay modes. In particular, some models with extended weak or hypercharge gauge groups that offer an explanation for the high mass of the top quark predict that such bosons preferentially couple to third-generation fermions [7].

This Letter presents the first search for high-mass resonances decaying into $\tau^+\tau^-$ pairs using the ATLAS detector [8]. The Sequential Standard Model (SSM) is a benchmark model that contains a heavy neutral gauge boson, $Z'_{\text{SSM}}$, with the same couplings to fermions as the $Z$ boson of the SM. This model is used to optimise the event selection of the search; limits on the cross section times branching fraction of $Z'$ resonances decaying into $\tau^+\tau^-$ pairs as a function of the resonance mass. As a result, $Z'$ bosons of the Sequential Standard Model with masses less than 1.40 TeV are excluded at 95% credibility.

2. Event samples

The data used in this search were recorded with the ATLAS detector in proton–proton ($pp$) collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV during the 2011 run of the Large Hadron Collider (LHC) [14]. The ATLAS detector consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer incorporating large superconducting toroid magnets. Each subdetector is divided into barrel and end-cap components.
Only data taken with pp collisions in stable beam conditions and with all ATLAS subsystems operational are used, resulting in an integrated luminosity of 4.6 fb\(^{-1}\). The data were collected using a combination of single-tau and ditau triggers, designed to select hadronic tau decays, and single-lepton triggers. The \(t_\text{had}t_\text{had}\) channel uses events passing either a ditau trigger with transverse energy (\(E_T\)) thresholds of 20 and 29 GeV, or a single-tau trigger with an \(E_T\) threshold of 125 GeV. The \(t_\mu_\text{had}\) and \(t_\tau_\text{had}\) channels use events passing a single-muon trigger with a transverse momentum (\(p_T\)) threshold of 18 GeV, which is supplemented by accepting events that pass a single-muon trigger with a \(p_T\) threshold of 40 GeV that operates only in the barrel region but does not require a matching inner detector track. The \(t_\tau_\text{had}\) channel uses events passing a single-electron trigger with \(p_T\) thresholds in the range 20–22 GeV, depending on the data-taking period. Events that pass the trigger are selected if the vertex with the largest sum of the squared track momenta has at least four associated tracks, each with \(p_T > 0.5\) GeV.

Monte Carlo (MC) simulation is used to estimate signal efficiencies and some background contributions. MC samples of background processes from QCD multijet events (enriched in special LHC tune [38]) are overlayed with an \(E_T\) momentum (\(\tau\)) threshold of 125 GeV. The \(t_\tau_\text{had}\) sample is generated with PYTHIA 6.425 [23], and tau lepton decays are generated with HERWIG 6.520 [16,17]. For these MC samples, the parton showering and hadronisation is performed by HERWIG 6.520 [18] interfaced to JIMMY 4.31 [19] for multiple parton interactions. Samples of \(s\)-channel and \(t\)-channel single-top-quark production are generated with AcerMC 3.8 [20], with the parton showering and hadronisation performed by PYTHIA 6.425 [21]. Samples of Z*\(_{\text{SM}}\) signal events are generated with PYTHIA 6.425, for eleven mass hypotheses ranging from 500 to 1750 GeV in steps of 125 GeV. In all samples photon radiation is performed by PHOTOS [22], and tau lepton decays are generated with TAUOLA [23]. The choice of parton distribution functions (PDFs) depends on the generator: CTeq6L1 [24] is used with ALPGEN, CT10 [25] with MC@NLO and MSTW2008 PDFs [28] with PYTHIA and AcerMC.

The Z/\(\gamma^*\) cross section calculated at next-to-next-to-leading order (NNLO) using PHOZFR [27] with MSTW2008 PDFs [28] is used to derive mass-dependent K-factors that are applied to the leading order Z/\(\gamma^*\) + jets and Z\(\rightarrow\) \(\tau\tau\) cross sections. The W + jets cross section is calculated at NNLO using FEWZ 2.0 [29,30]. The \(t\bar{t}\) cross section is calculated at approximate NNLO [31–33]. The cross sections for single-top production are calculated at next-to-next-to-leading logarithm for the \(s\)-channel [34] and approximate NNLO for \(t\)-channel and Wt production modes [35].

The detector response for each MC sample is simulated using a detailed GEANT4 [36] model of the ATLAS detector and subdetector-specific digitisation algorithms [37]. As the data are affected by the detector response to multiple pp interactions occurring in the same or in neighbouring bunch crossings (referred to as pile-up), minimum-bias interactions generated with PYTHIA 6.425 (with a specific LHC tune [38]) are overlaid on the generated signal and background events. The resulting events are re-weighted so that the distribution of the number of minimum-bias interactions per bunch crossing agrees with data. All samples are simulated with more than twice the effective luminosity of the data, except W + jets, where an equivalent of approximately 1.5 fb\(^{-1}\) is simulated.

3. Physics object reconstruction

Muon candidates are reconstructed by combining an outer detector track with a track from the muon spectrometer. They are required to have \(p_T > 10\) GeV and \(|\eta| < 2.5\).

1. Muon quality criteria are applied in order to achieve a precise measurement of the muon momentum and reduce the misidentification rate [39]. These quality requirements correspond to a muon reconstruction and identification efficiency of approximately 95%.

2. Electrons are reconstructed by matching clustered energy deposits in the EM calorimeter to tracks reconstructed in the inner detector [40]. The electron candidates are required to have \(p_T > 15\) GeV and to be within the fiducial volume of the inner detector, \(|\eta| < 2.47\). The transition region between the barrel and end-cap EM calorimeters, with \(1.37 < |\eta| < 1.52\), is excluded. The candidates are required to pass quality criteria based on the expected calorimeter shower shape and amount of radiation in the transition radiation tracker. These quality requirements correspond to an electron identification (ID) efficiency of approximately 90%.

3. Electrons and muons are considered isolated if they are away from large deposits of energy in the calorimeter, or tracks with large \(p_T\) consistent with originating from the same vertex.

Jets are reconstructed using the anti-\(k_t\) algorithm [41,42] with a radius parameter value of 0.4. The algorithm uses reconstructed, noise-suppressed clusters of calorimeter cells [43]. Jets are calibrated to the hadronic energy scale with correction factors based on simulation and validated using test-beam and collision data [44]. All jets are required to have \(p_T > 25\) GeV and \(|\eta| < 4.5\). For jets within the inner detector acceptance (\(|\eta| < 2.4\)), the jet vertex fraction is required to be at least 0.75; the jet vertex fraction is defined as the sum of the \(p_T\) of tracks associated with the jet and consistent with originating from the selected primary vertex, divided by the sum of the \(p_T\) of all tracks associated with the jet. This requirement reduces the number of jets that originate from pile-up or are heavily contaminated by it. Events are discarded if a jet is associated with out-of-time activity or calorimeter noise [45].

Candiates for hadron tau decays are defined as jets with either one or three associated tracks reconstructed in the inner detector. The kinematic properties of the tau candidate are reconstructed from the visible tau lepton decay products (all products excluding neutrinos). The tau charge is reconstructed from the sum of the charges of the associated tracks and is required to be \(\pm 1\). The charge misidentification probability is found to be negligible.

Hadronic tau decays are identified with a multivariate algorithm that employs boosted decision trees (BDTs) to discriminate against quark- and gluon-initiated jets using shower shape and tracking information [46]. Working points with a tau identification efficiency of about 50% (medium) for the \(t_\mu_\text{had}\) and \(t_\tau_\text{had}\) channels and 60% (loose) for the \(t_\text{had}t_\text{had}\) channel are chosen, leading to a rate of false identification for quark- and gluon-initiated jets of a few percent [47]. Tau candidates are also required to have \(p_T > 35\) GeV and to be in the fiducial volume of the inner detector, \(|\eta| < 2.47\).
from the highest-
one jet. The jet requirement suppresses
with magnitude
of priority: muons, electrons, tau candidates and jets. The missing
transverse momentum (with magnitude
of pseudorapidity region corresponds to a gap in the trans-
novation track that reduces the power of electron/pion discrim
ation. In the \( \tau_\tau \) channel, tau candidates are also re-
quired to pass an electron veto using BDTs.

Geometric overlap of objects with \( \Delta R < 0.2 \) is resolved by se-
lcting only one of the overlapping objects in the following order
of priority: muons, electrons, tau candidates and jets. The missing

4. Event selection

Selected events in the \( \tau_\tau \) channel must contain at least
two oppositely-charged tau candidates with \( p_T > 50 \) GeV and no

selected events in the \( \tau_\tau \) channels must contain exactly
one isolated muon with \( p_T > 25 \) GeV or an isolated electron with

\( p_T > 30 \) GeV; no additional electrons with \( p_T > 15 \) GeV or muons with

\( p_T > 4 \) GeV; and exactly one tau candidate with \( p_T > 35 \) GeV.
The angle between the lepton and tau candidate in the transverse
plane must be greater than 2.7 radians, and the pair must have

For the \( \tau_\tau \) channel, the \( Z \rightarrow e\mu \) and multijet contribu-
tions are reduced to a negligible level by requiring \( E_T^{\text{miss}} > 30 \) GeV. The

\( W + \text{jets} \) background is suppressed by requiring the transverse
mass, \( m_T \), of the electron–\( E_T^{\text{miss}} \) system, defined as

\[
m_T = \sqrt{2p_Te_T^{\text{miss}} (1 - \cos \Delta \phi)},
\]

where \( \Delta \phi \) is the angle between the lepton and \( E_T^{\text{miss}} \) in the trans-
verse plane, to be less than 50 GeV.

Selected events in the \( \tau_\mu \) channel must contain exactly one
isolated muon with \( p_T > 25 \) GeV and one isolated electron with

\( p_T > 35 \) GeV and opposite electric charge, no additional electrons with

\( p_T > 15 \) GeV or muons with \( p_T > 10 \) GeV and not more than

one jet. The jet requirement suppresses \( \tau \) events, which typically

\( Z \rightarrow \ell\ell \rightarrow \tau \tau \) events, are modelled with data-driven
techniques involving \textit{fake factors}, which parameterise the rate for
lepton candidates in jets to pass lepton isolation or jets to pass tau
identification, respectively. The remaining background is estimated
using simulation.

The dominant background processes in the \( \tau_\tau \) channel are

The shape of the \( m_T^{\text{tot}} \) distribution for the multijet background is
estimated using events that pass the standard event selection,
but have two selected \( \tau_\tau \) candidates with the same electric
charge and with \( m_T^{\text{tot}} > 200 \) GeV to avoid the low \( m_T^{\text{tot}} \) region
which is affected by the tau \( p_T \) threshold. For a low-mass sig-
nal with \( m_Z^2 \leq 625 \) GeV, a lower bound of 160 GeV is used, as

table 1

<table>
<thead>
<tr>
<th>( m_T ) (GeV)</th>
<th>500</th>
<th>625</th>
<th>750</th>
<th>875</th>
<th>1000</th>
<th>1125</th>
<th>( \geq 1250 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_T^{\text{miss}}^{\text{tot}} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{Jet} )</td>
<td>350</td>
<td>400</td>
<td>500</td>
<td>500</td>
<td>650</td>
<td>650</td>
<td>700</td>
</tr>
<tr>
<td>( \tau_\mu )</td>
<td>400</td>
<td>400</td>
<td>500</td>
<td>500</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>( \tau_\tau )</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>( \tau_{\mu\tau} )</td>
<td>300</td>
<td>350</td>
<td>350</td>
<td>350</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>
discussed below. This control region has only 2\% contamination from other background processes and negligible signal contamination. The $m^{\text{tot}}_T$ distribution is modelled by performing an unbinned maximum likelihood fit to the data in the control region using the following function:

$$f(m^{\text{tot}}_T | p_0, p_1, p_2) = p_0 \cdot (m^{\text{tot}}_T)^{p_1} + p_2 \log(m^{\text{tot}}_T),$$  \hspace{1cm} (4)$$

where $p_0$, $p_1$, and $p_2$ are free parameters. The integral of the fitted function in the high-mass tail matches the number of observed events well for any choice of the $m^{\text{tot}}_T$ threshold, and the function models the high-mass tail well in a simulated dijet sample enriched in high-mass events. The statistical uncertainty is estimated using pseudo-experiments and increases monotonically from 12\% to 83\% with increasing $m^{\text{tot}}_T$ threshold. The systematic uncertainty due to the choice of the fitting function is evaluated using alternative fitting functions and ranges from 1\% to 7\%. The multijet model is normalised to data that pass all analysis requirements but have $m^{\text{tot}}_T$ in the range 200–250 GeV. For the low-mass points with $m_T \leq 625$ GeV, the low-$m^{\text{tot}}_T$ side-band is lowered to 160–200 GeV to keep signal contamination negligible. Both side-bands have a maximum contamination of 5\% from other background processes, which is subtracted, and negligible contamination from signal. The statistical uncertainty from the normalisation ranges from 2\% to 5\%. Systematic uncertainties affecting the normalisation of the background processes are propagated when performing the subtraction but have a negligible effect.

5.2. Multijet background in the $\tau_{\text{lep}}\tau_{\text{had}}$ channels

The background from multijet events is negligible at high $m^{\text{tot}}_T$, but it is important to estimate its contribution to model the inclusive mass distribution. Multijet events are exceptional among the background processes because the muons and electrons produced in heavy-flavour decays or the light-flavour hadrons falsely identified as electrons, are typically not isolated in the calorimeter but produced in jets. To estimate the multijet background, events in the data that fail lepton isolation are weighted event-by-event, with fake factors for lepton isolation measured from data in a multijet-rich control region (multijet-CR). The multijet-CR is defined by requiring exactly one selected lepton, as in Section 4, but without the isolation requirement; at least one tau candidate that fails the BDT ID; no tau candidates that pass the BDT ID; $E^{\text{miss}}_T < 30$ GeV for the $\tau_{\text{had}}$ channel; $E^{\text{miss}}_T > 15$ GeV for the $\tau_{\text{lep}}\tau_{\text{had}}$ channel; and the transverse mass formed by the lepton and $E^{\text{miss}}_T$, $m_T(L, E^{\text{miss}}_T)$, to be less than 30 GeV. For the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, where the multijet contribution is dominated by $b$-quark-initiated jets, the muon is additionally required to have a transverse impact parameter of $d_0(\mu) > 0.8$ mm with respect to the primary vertex, which increases the purity of the multijet control region. The leptons in the multijet control region are divided into those that pass (isolated) and a subset that fail (anti-isolated) the isolation requirements. In the $\tau_{\text{lep}}\tau_{\text{had}}$ channel the anti-isolated sample includes all muons that fail isolation, while in the $\tau_{\text{had}}$ channel, the anti-isolation requirement is tightened to reduce contamination from real isolated electrons. Isolation fake factors, $f_{\text{iso}}$, are
defined as the number of isolated leptons in the data, \(N_{\text{iso}}\), divided by the number of anti-isolated leptons, \(N_{\text{anti-iso}}\), binned in \(p_T\) and \(\eta\):

\[
f_{\text{iso}}(p_T, \eta) = \frac{N_{\text{iso}}(p_T, \eta)}{N_{\text{anti-iso}}(p_T, \eta)} \bigg|_\text{multijet-CR}.
\]

Contamination from real isolated leptons is estimated using simulation and subtracted from \(N_{\text{iso}}\) (\(\sim3\%\) for \(\tau\tau\) had and \(\sim25\%\) for \(\tau\bar{\tau}\) had). The number of multijet events passing lepton isolation, \(N_{\text{multijet}}\), is predicted by weighting the events with anti-isolated leptons by their fake factor:

\[
N_{\text{multijet}}(p_T, \eta, x) = f_{\text{iso}}(p_T, \eta) \left( N_{\text{anti-iso}}(p_T, \eta, x) - N_{\text{anti-iso}}(p_T, \eta, x) \right).
\]

The shape of the multijet background in a given kinematic variable, \(x\), is modelled from the events in the data with anti-isolated leptons, \(N_{\text{data}}\), corrected by subtracting the expected contamination from other background processes predicted with MC simulation, \(N_{\text{anti-iso}}\).

This method assumes that the ratio of the number of isolated leptons to the number of anti-isolated leptons in multijet events is not strongly correlated with the requirements used to enrich the multijet control sample. This assumption has been verified by varying the \(E_{\text{miss}}^\tau\) and \(d_0\) selection criteria used to define the multijet control region. A conservative 100% systematic uncertainty on the isolation fake factor is assumed, but this has negligible effect on the sensitivity because the expected multijet background is less than a percent of the total background in both the \(\tau\nu\) had and \(\tau\tau\) had channels.

### 5.3. \(W + \text{jets} \) background in the \(\tau_{\text{lep}}\) CR channels

The \(W + \text{jets}\) background is estimated using a technique similar to the multijet estimate, where tau candidates that fail the BDT ID are weighted event-by-event with fake factors for jets to pass the BDT ID in \(W + \text{jets}\) events. A high purity \(W + \text{jets} \) control region (W-CR) is defined by selecting events that have exactly one isolated lepton, as in Section 4; at least one tau candidate that is not required to pass the BDT ID; and \(m_T(\ell, E_{\text{miss}}^\tau)\) between 70 and 200 GeV. For the \(\tau\tau\) had channel, the tau candidate is additionally required to pass the electron veto. Tau ID fake factors, \(f_\tau\), are defined as the number of tau candidates that pass the BDT ID, \(N_{\text{pass}}\), divided by the number that fail, \(N_{\text{fail}}\), binned in \(p_T\) and \(\eta\):

\[
f_\tau(p_T, \eta) = \frac{N_{\text{pass}} \tau-ID (p_T, \eta)}{N_{\text{fail}} \tau-ID (p_T, \eta)} \bigg|_{\text{W-CR}}.
\]

The number of \(W + \text{jets} \) events passing the BDT ID, \(N_{W+\text{jets}}\), is predicted by weighting the events that fail the BDT ID by their fake factor:

\[
N_{W+\text{jets}}(p_T, \eta, x) = f_\tau(p_T, \eta) \left( N_{\text{data}} \tau-ID (p_T, \eta, x) - N_{\text{data}} \tau-ID (p_T, \eta, x) \right) - N_{\text{multijet}} \tau-ID (p_T, \eta, x).
\]

The shape of the \(W + \text{jets}\) background is modelled using events in the data that failed the BDT ID, \(N_{\text{data}}\), with the multijet contamination, \(N_{\text{multijet}} \tau-ID (p_T, \eta, x)\), estimated from simulation, subtracted. A 30% systematic uncertainty on the fake factors is assigned by comparing the fake factors to those measured in a data sample enriched in \(Z + \text{jets}\) instead of \(W + \text{jets}\), which provides a sample of jets with a similar quark/gluon fraction [49]. This background estimation method relies on the assumption that the tau identification fake factors for \(W + \text{jets}\) events are not strongly correlated with the selection used to define the \(W + \text{jets} \) control region. This assumption has been verified by varying the \(m_T\) selection criterion used to define the \(W + \text{jets} \) control region, resulting in a few percent variation, which is well within the systematic uncertainty.

### 6. Systematic uncertainties

Systematic effects on the contributions of signal and background processes estimated from simulation are discussed in this section. These include theoretical uncertainties on the cross sections of simulated processes and experimental uncertainties on the trigger, reconstruction and identification efficiencies; on the energy and momentum scales and resolutions; and on the measurement of the integrated luminosity. For each source of uncertainty, the correlations across analysis channels, as well as the correlations between signal and background, are taken into account. Uncertainties on the background contributions estimated from data have been discussed in their respective sections.

The overall uncertainty on the \(Z\) signal and the \(Z\gamma^* \rightarrow \tau\tau\) background due to PDFs, \(\alpha_S\), and scale variations is estimated to be \(12\%\) at 1.5 TeV, dominated by the PDF uncertainty [12]. The uncertainty is evaluated using PDF error sets, and the spread of the variations covers the difference between the central values obtained with the CTEQ and MSTW PDF sets. Additionally, for \(Z\gamma^* \rightarrow \tau\tau\), a systematic uncertainty of \(10\%\) is attributed to electroweak corrections [50]. This uncertainty is not considered for the signal as it is strongly model-dependent. An uncertainty of 4–5% is assumed for the inclusive cross section of the single gauge boson and diboson production mechanisms and a relative uncertainty of 24% is added in quadrature per additional jet, due to the irreducible Berends-scaling uncertainty [51,52]. For \(t\bar{t}\) and single top-quark production, the QCD scale uncertainties are in the range of 3–6% [35,53,54]. The uncertainties related to the proton PDFs, including those arising from the choice of PDF set, amount to 8% for the predominantly gluon-initiated processes such as \(t\bar{t}\) and 4% for the predominant quark-initiated processes at low mass, such as on-shell single gauge boson and diboson production [25,28,40,57].

The uncertainty on the integrated luminosity is 3.9% [58,59]. The efficiencies of the electron, muon and hadronic tau triggers are measured in data and are used to correct the simulation. The associated systematic uncertainties are typically 1–2% for electrons and muons, 2.5% for the ditau trigger and 5% for the high-\(p_T\) single-tau trigger. Differences between data and simulation in the reconstruction and identification efficiencies of electrons, muons, and hadronic tau decays are taken into account, as well as the differences in the energy and momentum scales and resolutions. The associated uncertainties for muons and electrons are typically <1%.

The systematic uncertainties on the identification efficiency of hadronic tau decays are estimated at low \(p_T\) from data samples enriched in \(W \rightarrow \tau\nu\) and \(Z \rightarrow \tau\tau\) events. At high \(p_T\), there are no abundant sources of real hadron tau decays to make an efficiency measurement. Rather, the fraction of jets that pass the tau identification is studied in high-\(p_T\) dijet events as a function of the jet \(p_T\), which indicates that there is no degradation in the modelling of the detector response as a function of the \(p_T\) of tau candidates. From these studies, an efficiency uncertainty of up to 8% is assigned to high-\(p_T\) tau candidates. The uncertainty on the jet-to-tau misidentification rate is 50%, determined from data-MC comparisons in \(W + \text{jets}\) events. The uncertainty on the electron-to-tau misidentification rate is 50–100%, depending on the pseudorapidity of the tau candidate, based on measurements made using a \(Z \rightarrow ee\) sample selected from data [47]. The energy scale uncertainty on taus and jets is evaluated based on the single-hadron response in
vector. The statistical uncertainty corresponds to the uncertainty due to limited sample size in the MC and control regions.

### Table 2

<table>
<thead>
<tr>
<th>Uncertainty [%]</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hh</td>
<td>µh</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Eff. and fake rate</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Energy scale and res.</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Theory cross section</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Luminosity</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Data-driven methods</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

the calorimeters [44,60]. In addition, the tau energy scale is validated in data samples enriched in $Z \rightarrow \tau \tau$ events. The systematic uncertainties related to the jet and tau energy scale and resolution are functions of $\eta$ and $p_T$, and are generally near 3%. These uncertainties are treated as fully correlated. Energy scale and resolution uncertainties on all objects are propagated to the $E_T^{miss}$ calculation. The uncertainty on the $E_T^{miss}$ due to clusters that do not belong to any reconstructed object is measured to be negligible in all channels.

Table 2 summarises the uncertainties on the estimated signal and total background contributions in each channel. For the background, the contribution from each uncertainty depends on the fraction of the background estimated with simulation. The dominant uncertainties on the background come from the multijet shape estimation and the tau energy scale uncertainty for $Z/\gamma^* \rightarrow \tau \tau$ events in the $\tau_{had}\tau_{had}$ channel, from the limited sample size and the fake factor estimate of the $W+J$ background in the $\tau_{lep}\tau_{had}$ channels and from the statistical uncertainty of the MC samples in the $\tau_{\tau_{\mu}}$ channel. The dominant uncertainty on the signal for the $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ channels comes from the tau identification efficiency and for the $\tau_{\tau_{\mu}}$ channel, from the statistical uncertainty on the MC samples.

### Table 3

Table 3 summarises the uncertainties on the estimated signal and total background contributions in each channel. For the background, the contribution from each uncertainty depends on the fraction of the background estimated with simulation. The dominant uncertainties on the background come from the multijet shape estimation and the tau energy scale uncertainty for $Z/\gamma^* \rightarrow \tau \tau$ events in the $\tau_{had}\tau_{had}$ channel, from the limited sample size and the fake factor estimate of the $W+J$ background in the $\tau_{lep}\tau_{had}$ channels and from the statistical uncertainty of the MC samples in the $\tau_{\tau_{\mu}}$ channel. The dominant uncertainty on the signal for the $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ channels comes from the tau identification efficiency and for the $\tau_{\tau_{\mu}}$ channel, from the statistical uncertainty on the MC samples.

### 7. Results and discussion

The numbers of observed and expected events including their total uncertainties, after the full selection in all channels, are summarised in Table 3. In all cases, the number of observed events is consistent with the expected Standard Model background. Therefore, upper limits are set on the production of a high-mass resonance decaying to $\tau^+\tau^-$ pairs.

The statistical combination of the channels employs a likelihood function constructed as the product of Poisson probability terms describing the total number of events observed in each channel. The Poisson probability in each channel is evaluated for the observed number of data events given the signal plus background expectation. Systematic uncertainties on the expected number of events are incorporated into the likelihood via Gaussian-distributed nuisance parameters. Correlations across channels are taken into account. A signal strength parameter multiplies the expected signal in each channel, for which a positive uniform prior probability distribution is assumed. Theoretical uncertainties on the signal cross section are not included in the calculation of the experimental limit as they are model-dependent.

The Bayesian 95% credibility upper limits are set on the cross section times branching fraction for a high-mass resonance decaying into a $\tau^+\tau^-$ pair as a function of the resonance mass, using the Bayesian Analysis Toolkit [61]. Figs. 2(a) and 2(b) show the limits for the individual channels and for the combination, respectively. The resulting 95% credibility lower limit on the mass of a $Z_{SSM}^*$ decaying to $\tau^+\tau^-$ pairs is 1.40 TeV, with an expected limit of 1.42 TeV. The observed and expected limits in the individual channels are, respectively: 1.26 and 1.35 TeV ($\tau_{had}\tau_{had}$); 1.07 and 1.10 TeV ($\tau_{\tau_{\mu}}$); 1.10 and 1.03 TeV ($\tau_{\tau_{\mu}}$); and 0.72 and 0.82 TeV ($\tau_{\tau_{\mu}}$).

The impact of the choice of the prior on the signal strength parameter has been evaluated by also considering the reference prior [62]. Use of the reference prior improves the mass limits by approximately 50 GeV. The impact of the vector and axial coupling strengths of the $Z^*$ has been investigated, as these can alter the fraction of the tau momentum carried by the visible decay products. For purely $V-A$ couplings, the limit on the cross section times $\tau^+\tau^-$ branching fraction is improved by $\sim 10\%$ over the mass range. For purely $V+A$ couplings, there is a mass-dependent degradation, from $\sim 15\%$ at high mass to $\sim 40\%$ at low mass. All variations lie within the $1\sigma$ band of the expected exclusion limit.

### 8. Conclusion

A search for high-mass ditau resonances has been performed using 4.6 fb$^{-1}$ of data collected with the ATLAS detector in $pp$ collisions at $\sqrt{s} = 7$ TeV at the LHC. The $\tau_{had}\tau_{had}$, $\tau_{\tau_{\mu}}$, $\tau_{\tau_{\mu}}$ and $\tau_{\tau_{\mu}}$ channels are analysed. The observed number of events in the high-transverse-mass region is consistent with the SM expectations.
Fig. 2. (a) The expected (dashed) and observed (solid) 95% credibility upper limits on the cross section times branching fraction for such resonances. The resulting lower limit on the mass of a $Z'$ decaying to $\tau^+\tau^-$ in the Sequential Standard Model is 1.40 TeV at 95% credibility, in agreement with the expected limit of 1.42 TeV in the absence of a signal.

(b) The expected and observed limits for the combination including 1σ and 2σ uncertainty bands. $Z_{\text{SM}}$ masses up to 1.40 TeV are excluded, in agreement with the expected limit of 1.42 TeV in the absence of a signal.

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