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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*"}

**Abstract**

This Letter presents a search for high-mass resonances decaying into $\tau^+\tau^-$ final states using proton-proton collisions at $\sqrt{s} = 7$ TeV produced by the Large Hadron Collider. The data were recorded with the ATLAS detector and correspond to an integrated luminosity of 4.6 fb$^{-1}$. No statistically significant excess above the Standard Model expectation is observed; 95% credibility upper limits are set 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.

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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 $\tau^+\tau^-$ branching fraction of a generic neutral resonance are reported.

Direct searches for high-mass ditau resonances have been performed previously by the CDF [9] and CMS [10] collaborations. The latter search sets the most stringent 95% confidence level limits and excludes $Z'_{\text{SSM}}$ masses below 1.4 TeV, with an expected limit of 1.1 TeV, using 4.9 fb$^{-1}$ of integrated luminosity at $\sqrt{s} = 7$ TeV. Indirect limits on $Z'$ bosons with non-universal flavour couplings have been set using measurements from LEP and LEP II [11] and translate to a lower bound on the $Z'$ mass of 1.09 TeV. For comparison, the most stringent limits on $Z'_{\text{SSM}}$ in the dielectron and dimuon decay channels combined are 2.2 TeV from ATLAS [12] and 2.3 TeV from CMS [13].

Tau leptons can decay into a charged lepton and two neutrinos ($\tau_{\text{lep}} = \tau_e$ or $\tau_\mu$), or hadronically ($\tau_{\text{had}}$), predominantly into one or three charged pions, a neutrino and often additional neutral pions. The $\tau_{\text{had}}$ ($\tau_{\text{had}}$ branching ratio, BR $= 42\%$), $\tau_\mu\tau_{\text{had}}$ (BR $= 23\%$), $\tau_e\tau_{\text{had}}$ (BR $= 23\%$) and $\tau_\mu\tau_\mu$ (BR $= 6\%$) channels are analysed. Due to the different dominant background contributions and signal sensitivities, each channel is analysed separately and a statistical combination is used to maximise the sensitivity.

While the expected natural width of the $Z'_{\text{SSM}}$ is small, approximately 3% of the $Z'$ mass, the mass resolution is 30–50% in $\tau^+\tau^-$ decay modes due to the undetected neutrinos from the tau decays. Therefore, a counting experiment is performed in all analysis channels from events that pass a high-mass requirement.

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 $\tau_{\text{had}}^{\text{had}}$ 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 $\tau_\mu$ and $\tau_e^\tau_\mu$ channels use events passing a single-muon trigger with a $p_T$ threshold 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 $W + j$ and $Z/\gamma^* + j$ (enriched in high-mass $Z/\gamma^* \rightarrow \tau\tau$) events are generated with ALPGEN 2.13 [15], including up to five additional partons. Samples of $t\bar{t}$, $Wt$ and diboson ($WW$, $WZ$, and $ZZ$) events are generated with MC@NLO 4.01 [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: CT10 [24] is used with ALPGEN, CT10 [25] with MC@NLO and MSTW2008 LO* [26] with PYTHIA and AcerMC.

The $Z/\gamma^*$ cross section calculated at next-to-next-to-leading order (NNLO) using PHOJET [27] with MSTW2008 PDFs [28] is used to derive mass-dependent $K$-factors that are applied to the leading order $Z/\gamma^* + j$ and $Z' \rightarrow \tau\tau$ cross sections. The $W + j$ 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 $W + j$, where an equivalent of approximately 1.5 $fb^{-1}$ is simulated.
are reduced to a negligible level by requiring one jet. The jet requirement suppresses two oppositely-charged tau candidates with opposite electric charge. The missing transverse momentum (with magnitude $E_{\text{miss}}$) is calculated from the vector sum of the transverse momenta of all high-$p_T$ objects reconstructed in the event, as well as a term for the remaining activity in the calorimeter [48]. Clusters associated with electrons, hadronic tau decays and jets are calibrated separately, with the remaining clusters calibrated at the EM energy scale.

### 4. Event selection

Selected events in the $\tau_{\text{had}}\tau_{\text{had}}$ channel must contain at least two oppositely-charged tau candidates with $p_T > 50$ GeV and no electrons with $p_T > 15$ GeV or muons with $p_T > 10$ GeV. If the event was selected by the ditau trigger, both tau candidates are required to be geometrically matched to the objects that passed the trigger. For events that pass only the single-tau trigger there is no ambiguity, so trigger matching is not required. If multiple tau candidates are selected, the two highest-$p_T$ candidates are chosen. The angle between the two tau candidates in the transverse plane must be greater than 2.7 radians.

Selected events in the $\tau_{\text{lep}}\tau_{\text{had}}$ 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 opposite electric charge.

For the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, the $Z \rightarrow e e$ and multijet contributions are reduced to a negligible level by requiring $E_{\text{T}}^{\text{miss}} > 30$ GeV. The $W +$ jets background is suppressed by requiring the transverse mass, $m_T$, of the electron-$E_{\text{T}}^{\text{miss}}$ system, defined as

$$m_T = \sqrt{2P_{T\ell}E_{T}^{\text{miss}}(1 - \cos \Delta \phi)},$$

where $\Delta \phi$ is the angle between the lepton and $E_{\text{T}}^{\text{miss}}$ in the transverse plane, to be less than 50 GeV.

Selected events in the $\tau_{\tau}\tau_{\mu}$ 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 $t\bar{t}$ events, which typically have higher jet multiplicity than the signal. The two leptons are required to be back-to-back in the transverse plane using the criterion $P_{T\mu}^{\text{vis}} < 10$ GeV, with

$$P_{T\mu}^{\text{vis}} = \vec{P}_{T\ell} + \vec{P}_{T\mu} \cdot \hat{\zeta},$$

where $\zeta$ is a unit vector along the bisector of the $e$ and $\mu$ momenta. This selection provides good suppression of the dijet and $t\bar{t}$ backgrounds. For $Z$ events, the $E_{\text{T}}^{\text{miss}}$ tends to point away from the highest-$p_T$ lepton, so the angle between the highest-$p_T$ lepton and $E_{\text{T}}^{\text{miss}}$ in the transverse plane is required to be greater than 2.6 radians.

The search in all channels is performed by counting events in signal regions with total transverse mass above thresholds optimised separately for each signal mass hypothesis in each channel to give the best expected exclusion limits (see Table 1). The total transverse mass, $m_{T}^{\text{tot}}$, is defined as the mass of the visible decay products of both tau leptons and $E_{\text{T}}^{\text{miss}}$, neglecting longitudinal momentum components and the tau lepton mass,

$$m_{T}^{\text{tot}} = \sqrt{2P_{T\tau}p_{T2}C + 2E_{T}^{\text{miss}}p_{T1}C_1 + 2E_{T}^{\text{miss}}p_{T2}C_2},$$

where $p_{T1}$ and $p_{T2}$ are the transverse momenta of the visible products of the two tau decays; $C$ is defined as $1 - \cos \Delta \phi$, where $\Delta \phi$ is the angle in the transverse plane between the visible products of the two tau decays; and $C_1$ and $C_2$ are defined analogously for the angles in the transverse plane between $E_{\text{T}}^{\text{miss}}$ and the visible products of the first and second tau decay, respectively. Figs. 1(a)-(d) show the $m_{T}^{\text{tot}}$ distribution after event selection in each channel.

### 5. Background estimation

The dominant background processes in the $\tau_{\text{had}}\tau_{\text{had}}$ channel are multijet production and $Z/\gamma^* \rightarrow \tau\tau$. Minor contributions come from $W(\rightarrow \tau\nu) +$ jets, $Z(\rightarrow \ell\ell) +$ jets ($\ell = e$ or $\mu$), $W(\rightarrow \ell\nu) +$ jets, $t\bar{t}$, single top-quark and diboson production. The shape of the multijet mass distribution is estimated from data that pass the full event selection but have two tau candidates of the same electric charge. The contribution is normalised to events that pass the full event selection but have low $m_{T}^{\text{tot}}$. All other background contributions are estimated from simulation.

The main background contributions in the $\tau_{\text{lep}}\tau_{\text{had}}$ channels come from $Z/\gamma^* \rightarrow \tau\tau$, $W +$ jets and diboson production, with minor contributions from $Z(\rightarrow \ell\ell) +$ jets, multijet and single top-quark events. The contributions involving fake hadronic tau decays from multijet and $W +$ jets events are modelled with data-driven techniques involving 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 $\tau_{\tau}\tau_{\mu}$ channel are $t\bar{t}$, $Z/\gamma^* \rightarrow \tau\tau$ and diboson production. Contributions from processes such as $Z(\rightarrow \mu\mu) +$ jets, $W +$ jets and $W/\gamma +$ jets, where a jet or photon is misidentified as an electron, are very small in the signal region. Multijet events are suppressed by tight lepton isolation criteria. Since background processes involving fake leptons make only minor contributions, all background contributions in the $\tau_{\tau}\tau_{\mu}$ channel are estimated using simulation. The MC estimates of the dominant background contributions are checked using high-purity control regions in data.

The following subsections describe the data-driven background estimates in more detail.

#### 5.1. Multijet background in the $\tau_{\text{had}}\tau_{\text{had}}$ channel

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 $\tau_{\text{had}}$ 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 signal with $m_{Z} \leq 625$ GeV, a lower bound of 160 GeV is used, as
discussed below. This control region has only 2% contamination from other background processes and negligible signal contamination. The $m_T^{\text{tot}}$ distribution is modelled by performing an unbinned maximum likelihood fit to the data in the control region using the following function:

$$f(m_T^{\text{tot}}|p_0, p_1, p_2) = p_0 \cdot (m_T^{\text{tot}})^{p_1} \cdot (1 + p_2 \log(m_T^{\text{tot}})),$$  \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 $m_T^{\text{tot}}$ 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 1% to 7%. The multijet model is normalised to data that pass all analysis requirements but have $m_T^{\text{tot}}$ in the range 200–250 GeV. For the low-mass points with $m_{Z'} \leq 625$ GeV, the low-$m_T^{\text{tot}}$ 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 $m_T^{\text{tot}}$, 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; $E_{miss} < 15$ GeV for the $\tau_\mu\tau_\text{had}$ channel, $E_{miss} < 30$ GeV for the $\tau_\tau\text{had}$ channel; and the transverse mass formed by the lepton and $E_{miss}$, $m_T(\ell, E_{miss})$, to be less than 30 GeV. For the $\tau_\tau\text{had}$ channel, where the multijet contribution is dominated by $b$-quark-initiated jets, the muon is additionally required to have a transverse impact parameter of $|d_0(m)| > 0.08$ 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 $\tau_\tau\text{had}$ channel the anti-isolated sample includes all muons that fail isolation, while in the $\tau_\mu\tau_\text{had}$ 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 \(\eta\):

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

(5)

Contamination from real isolated leptons is estimated using simulation and subtracted from \(N_{\text{iso}}\) (∼3% for \(\tau\) had and ∼25% for \(\tau\) T 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:

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

(6)

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 \(E^\text{miss}\) 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 \(\tau\) had and \(\tau\) T had channels.

5.3. \(W + \text{jets}\) background in the \(\tau\) \(\text{lep}\) \(\tau\) \(\text{had}\) 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 passes the BDT ID is defined as the number of tau candidates that pass the BDT ID, \(N_{\text{T}}\), divided by the number that fail, \(N_{\text{fail}}\), binned in \(p_T\) and \(\eta\):

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

(7)

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:

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

(8)

The shape of the \(W + \text{jets}\) background is modelled using events in the data that failed the BDT ID, \(N_{\text{fail}}\), with the multijet contamination, \(N_{\text{multijet}}\), 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 \(m_\tau\) 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 \(Z'\rightarrow\tau\tau\) 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 \(Z'\rightarrow\tau\tau\), 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 tt 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 tt and 4% for the predominantly quark-initiated processes at low mass, such as on-shell single gauge boson and diboson production [25,28,55–57].

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 hadronic 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 + jet 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
the calorimeters [44,60]. In addition, the tau energy scale is validated in data samples enriched in the calorimeters. The 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 total uncertainties, after the full selection in all channels, are summed.

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 the $W+\text{jets}$ background. The contribution from each uncertainty depends on the fraction of the tau momentum carried by the visible decay products.

### Table 2

<table>
<thead>
<tr>
<th>Uncertainty [%]</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\eta h$</td>
<td>$\mu h$</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
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<td>2</td>
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<tr>
<td>Eff. and fake rate</td>
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<td>10</td>
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<tr>
<td>Energy scale and res.</td>
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<td>5</td>
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<td>Theory cross section</td>
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<td>6</td>
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<tr>
<td>Luminosity</td>
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<td>4</td>
</tr>
<tr>
<td>Data-driven methods</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

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.

### Table 3

<table>
<thead>
<tr>
<th>$m_Z$ [GeV]</th>
<th>$m_{\tau\tau}$ threshold [GeV]</th>
<th>$\tau_T\tau_T$</th>
<th>$\tau_T\tau_T$</th>
<th>$\tau_T\tau_T$</th>
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</thead>
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<td>1250</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$Z/\gamma^* \rightarrow \tau\tau$</td>
<td>0.73 ± 0.23</td>
<td>0.36 ± 0.06</td>
<td>0.57 ± 0.11</td>
<td>0.55 ± 0.07</td>
</tr>
<tr>
<td>$W+\text{jets}$</td>
<td>&lt; 0.03</td>
<td>0.28 ± 0.22</td>
<td>0.8 ± 0.4</td>
<td>0.33 ± 0.10</td>
</tr>
<tr>
<td>$Z(\rightarrow \ell\ell) + \text{jets}$</td>
<td>&lt; 0.01</td>
<td>&lt; 0.1</td>
<td>0.13 ± 0.09</td>
<td>0.30 ± 0.22</td>
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<tr>
<td>$t\bar{t}$</td>
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<td>Single top</td>
<td>&lt; 0.01</td>
<td>0.19 ± 0.18</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Multijet</td>
<td>0.24 ± 0.15</td>
<td>&lt; 0.01</td>
<td>&lt; 0.1</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Total expected background</td>
<td>0.97 ± 0.27</td>
<td>1.4 ± 0.4</td>
<td>1.6 ± 0.5</td>
<td>3.6 ± 0.4</td>
</tr>
<tr>
<td>Events observed</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Expected signal events</td>
<td>6.3 ± 1.1</td>
<td>5.5 ± 0.7</td>
<td>5.0 ± 0.5</td>
<td>6.72 ± 0.26</td>
</tr>
<tr>
<td>Signal efficiency (%)</td>
<td>4.3</td>
<td>1.1</td>
<td>1.0</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Fig. 2. (a) The expected (dashed) and observed (solid) 95% credibility upper limits on the cross section times \( \tau^+ \tau^- \) branching fraction, in the \( t\bar{t}\) channel, as well as the \( \tau\tau\mu\tau \) and \( \tau\tau\tau \) decay channels for the combination. The expected \( Z_{SM} \) production cross section and its corresponding theoretical uncertainty (dotted) are also included. (b) The expected and observed limits for the combination including 1\( \sigma \) and 2\( \sigma \) uncertainty bands. \( Z_{SM} \) 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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ATLAS Collaboration


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