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


Published in:
Physics Letters B

DOI:
10.1016/j.physletb.2013.01.040

Link to publication

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).
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.

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 $\tau_{had}$/$\tau_{had}$ 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 $\tau_\mu$/$\tau_\mu$ and $\tau_\tau$/$\mu_\tau$ 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 $\tau_\tau$/$\tau_\mu$ 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 various production modes are generated with ALPGEN 2.13 [15], including up to five additional partons. Samples of $W$, $Wt$ 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 $Z^\gamma$/$\gamma^*$ 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 MRST2007 LO [26] with PYTHIA and AcerMC.

The $Z^\gamma$/$\gamma^*$ cross section calculated at next-to-next-to-leading order (NNLO) using PHOZPR [27] with MSTW2008 PDFs [28] is used to derive mass-dependent K-factors that are applied to the leading order $Z^\gamma$/$\gamma^*$ + jets and $Z^\gamma$ → $\tau\tau$ 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 GRANT4 [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 a muon 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%.

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%. 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.² In the $\tau_{had}$/$\tau_{had}$ channel, isolated electrons are also required to pass a tighter identification requirement corresponding to an efficiency of approximately 80%.

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].

Candidates for hadronic 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 ±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 $\tau_\mu$/$\tau_\mu$ and $\tau_\tau$/$\tau_\mu$ channels and 60% (loose) for the $\tau_\mu$/$\tau_\mu$ 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, $|\eta| < 2.47$

---

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = \ln(\tan(\theta/2))$. Separation in the $\eta$–φ plane is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

² Lepton isolation is defined using the sum of the $E_T$ deposited in calorimeter cells within $\Delta R < 0.2$ of the lepton, $E_T^{\ell}$, and the scalar sum of the $p_T$ of tracks with $p_T > 0.5$ GeV consistent with the same vertex as the lepton and within $\Delta R < 0.4$. Muons are considered isolated if they have $p_T^{\ell} > p_T^{\tau} < 4.5$ GeV and $p_T^{\ell}/p_T^{\tau} < 6%$ in the $\tau_\mu$/$\tau_\mu$ channel; isolated electrons must have $p_T^{\ell}/p_T^{\tau} < 5%$ and $E_T^{\ell}/p_T^{\tau} < 5%$ if $p_T < 100$ GeV or $E_T^{\ell}/p_T^{\tau} < 5%$ otherwise ($E_T^{\ell}/p_T^{\tau} < 6%$ and $p_T^{\ell}/p_T^{\tau} < 8%$ in the $\tau_\tau$/$\tau_\mu$ channel).
from the highest-\(\tau\) plane, to be less than 50 GeV. The angle between the tau candidates in the transverse plane must be greater than 2.7 radians, and the pair must have higher jet multiplicity than the signal. The two leptons are required to be back-to-back in the transverse plane using the criterion 

\[
\cos \Delta \phi = \frac{\mathbf{p}_{T \ell} \cdot \mathbf{p}_{T\tau}}{p_{T \ell} p_{T\tau}} < 0.5. \tag{1}
\]

where \(\Delta \phi\) is the angle between the lepton and lepton candidates in the transverse plane. This selection provides good suppression of the diboson background and is estimated using events 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 \(m_{\ell\ell}\). All other background contributions are estimated from simulation.

The main background contributions in the \(\tau_\mu\tau_\mu\) channel are \(Z/\gamma^*\rightarrow\ell\ell, W+\ell\ell, W+\mu\mu, W+\tau\tau\) and diboson production, with minor contributions from \(Z\rightarrow\ell\ell\) and \(\mu\mu\) and single top-quark production. The contributions involving fake hadronic tau decays from multijet and \(W+\mu\mu\) events are modelled with data-driven techniques involving fake factors, which parametrise 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 \(\tau_{\ell\mu}\) channel are \(Z/\gamma^*\rightarrow\ell\ell, W+\mu\mu, W+\tau\tau\) and diboson production. Production from processes such as \(Z\rightarrow\mu\mu\) and \(W+\mu\mu\) and \(W+\tau\tau\) production, 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 \(\tau_{\ell\mu}\) 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 \(\tau_\mu\tau_\mu\) channel

The shape of the \(m_{\tau\tau}\) distribution for the multijet background is estimated using events that pass the standard event selection, but have two selected \(\tau_\mu\tau_\mu\) candidates with the same electric charge and with \(m_{\tau\tau}\) > 200 GeV to avoid the low \(m_{\tau\tau}\) region which is affected by the tau PDG threshold. For a low-mass signal with \(m_{Z'} \lesssim 625\) 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:

\[
f(m_T^{\text{tot}}|p_0, p_1, p_2) = p_0 \cdot (m_T^{\text{tot}})^{p_1} p_2 \log(m_T^{\text{tot}}),
\]

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 12% to 83% with increasing \(m_T^{\text{tot}}\) 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 \(m_T^{\text{tot}}\) in the range 200–250 GeV. For the low-mass points with \(m_T < 625\) 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 \(\tau_\mu\tau_\mu\) 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; \(E_T^{\text{miss}} < 15\) GeV for the \(\tau_\mu\tau_\mu\) channel, \(E_T^{\text{miss}} < 30\) GeV for the \(\tau_\tau\) channel; and the transverse mass formed by the lepton and \(E_T^{\text{miss}}, m_T^{\text{lep}}(E_T^{\text{miss}})\), to be less than 30 GeV. For the \(\tau_\mu\tau_\mu\) channel, where the multijet contribution is dominated by \(b\)-quark-initiated jets, the muon is additionally required to have a transverse impact parameter of \(|d_0(\mu)| > 0.08\) 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 \(\tau_\tau\) channel the anti-isolated sample includes all muons that fail isolation, while in the \(\tau_\mu\tau_\mu\) channel, the anti-isolation requirement is tightened to reduce contamination from real isolated electrons. Isolation fake factors, \(f_{\text{id}}\), 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 $\eta$:

$$f_{\text{iso}}(p_T, \eta) \equiv \frac{N_{\text{iso}}(p_T, \eta)}{N_{\text{anti-iso}}(p_T, \eta)} \mid_{\text{multijet-CR}}. \quad (5)$$

Contamination from real isolated leptons is estimated using simulation and subtracted from $N_{\text{iso}}$ (~3% for $\tau_\nu$-had and ~25% for $\tau_\tau$-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:

$$N_{\text{multijet}}(p_T, \eta, x) = f_{\text{iso}}(p_T, \eta)(N_{\text{anti-iso}}(p_T, \eta, x) - N_{\text{anti-iso}}(p_T, \eta, x)). \quad (6)$$

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 $E_{\text{T}}^{\text{miss}}$ and $d_{\text{0}}$ 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 $\tau_{\text{lep}}$-$\tau_{\text{had}}$ 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 is not required to pass the BDT ID; and one tau candidate associated with the electron veto. Tau ID fake factors, $f_{\tau}$, are defined as the number of tau candidates that pass the BDT ID, $N_{\text{pass}}(p_T, \tau_{\text{ID}})$, divided by the number that fail, $N_{\text{fail}}(p_T, \tau_{\text{ID}})$, binned in $p_T$ and $\eta$:

$$f_{\tau}(p_T, \eta) \equiv \frac{N_{\text{pass}}(p_T, \tau_{\text{ID}})(p_T, \eta)}{N_{\text{fail}}(p_T, \tau_{\text{ID}})(p_T, \eta)} \mid_{\text{W-CR}}. \quad (7)$$

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:

$$N_{W+\text{jets}}(p_T, \eta, x) = f_{\tau}(p_T, \eta)(N_{\text{data}}(p_T, \tau_{\text{ID}}) - N_{\text{data}}(p_T, \tau_{\text{ID}}, x)),$$

$$- N_{\text{fail}}(p_T, \tau_{\text{ID}})(p_T, \eta, x) - N_{\text{multijet}}(p_T, \tau_{\text{ID}})(p_T, \eta, x). \quad (8)$$

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, $N_{\text{multijet}}(p_T, \tau_{\text{ID}})$ (estimated from data), and other contaminations, $N_{\text{fail}}(p_T, \tau_{\text{ID}})$ (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 $Z\gamma^* \rightarrow \tau\tau$ 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 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-$p_T$ ditau 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
Table 2

<table>
<thead>
<tr>
<th>Uncertainty [%]</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hh µh</td>
<td>eh ep µµ</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
<td>1 2</td>
<td>3 5 20 23</td>
</tr>
<tr>
<td>Eff. and rate</td>
<td>16 10 8</td>
<td>1 12 16 3</td>
</tr>
<tr>
<td>Energy scale and res.</td>
<td>5 7 6 2</td>
<td>3 8 5</td>
</tr>
<tr>
<td>Theory cross section</td>
<td>8 6 6 5</td>
<td>4 4 5</td>
</tr>
<tr>
<td>Luminosity</td>
<td>4 4 4 4</td>
<td>2 2 4</td>
</tr>
<tr>
<td>Data-driven methods</td>
<td>- - -</td>
<td>6 16 -</td>
</tr>
</tbody>
</table>

The calorimeters [44,60]. In addition, the tau energy scale is validated in data samples enriched in Z → ττ events. The systematic uncertainties related to the jet and tau energy scale and resolution are functions of η and pT, 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 summarised in Table 2. In all cases, the number of observed events is the calculated 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.

Bayesian 95% credibility upper limits are set on the production of a high-mass resonance decaying into a τ+τ− 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 τ+τ− 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 (τhadτhad); 1.07 and 1.06 TeV (τlepτhad); 1.10 and 1.03 TeV (ττhad); and 0.72 and 0.82 TeV (ττμ).

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 τ+τ− branching fraction is improved by ~10% over the mass range. For purely V + A couplings, there is a mass-dependent degradation, from ~15% at high mass to ~40% at low mass. All variations lie within the 1σ 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 √s = 7 TeV at the LHC. The σ(pp → Z*SSM) → ττ × 1/5.55.

Table 3

<table>
<thead>
<tr>
<th>mZ* [GeV]</th>
<th>mT [GeV]</th>
<th>mT [GeV]</th>
<th>mT [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1250</td>
<td>700</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Z/γ* → ττ</td>
<td>0.73 ± 0.23</td>
<td>0.36 ± 0.06</td>
<td>0.57 ± 0.11</td>
</tr>
<tr>
<td>W + jets</td>
<td>&lt; 0.03</td>
<td>0.28 ± 0.22</td>
<td>0.8 ± 0.4</td>
</tr>
<tr>
<td>Z(→ℓ±ℓ′) + jets</td>
<td>&lt; 0.01</td>
<td>&lt; 0.1</td>
<td>0.13 ± 0.09</td>
</tr>
<tr>
<td>t̄t</td>
<td>&lt; 0.02</td>
<td>0.33 ± 0.15</td>
<td>0.06 ± 0.03</td>
</tr>
<tr>
<td>Diboson</td>
<td>&lt; 0.01</td>
<td>0.19 ± 0.18</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Single top</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Multijet</td>
<td>0.24 ± 0.15</td>
<td>&lt; 0.01</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>
</tr>
<tr>
<td>Events observed</td>
<td>2</td>
<td>1</td>
<td>0</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>
</tr>
<tr>
<td>Signal efficiency (%)</td>
<td>4.3</td>
<td>1.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>
tation. Limits are set 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.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CF, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MES FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; CSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR, MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.
ATLAS Collaboration

Department of Physics, University of Johannesburg, Johannesburg, South Africa

School of Physics, University of the Witwatersrand, Johannesburg, South Africa

Department of Physics, Stockholm University, The Oskar Klein Centre, Stockholm, Sweden

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States

Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

Department of Physics, University of Toronto, Toronto, ON, Canada

TRIUMF, Vancouver, BC, Department of Physics and Astronomy, York University, Toronto, ON, Canada

Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford, MA, United States

Centre de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States

Department of Physics, University of Illinois, Urbana, IL, United States

Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States

Department of Physics, The University of Michigan, Ann Arbor, MI, United States

Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.

Institute of Physics, Jagiellonian University, Krakow, Poland

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France.

Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.

Also at Dep. Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.

Also at Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada

Also at Department of Physics, University of Windsor, Madison, WI, United States

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, CT, United States

Yerevan Physics Institute, Yerevan, Armenia

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

Also at Department of Physics, UASLP, San Luis Potosi, Mexico.

Also at Department of Physics, University of Johannesburg, Johannesburg, South Africa.

Also at TRIUMF, Vancouver, BC, Canada.

Also at Department of Physics, California State University, Fresno, CA, United States.

Also at Novosibirsk State University, Novosibirsk, Russia.

Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

Also at Department of Physics, UASLP, San Luis Potosi, Mexico.

Also at Università di Napoli Parthenope, Napoli, Italy.

Also at Instituto de Particle Physics (IPP), Canada.

Also at Department of Physics, Middle East Technical University, Ankara, Turkey.

Also at Louisiana Tech University, Ruston, LA, United States.

Also at Dep. Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.

Also at Department of Physics and Astronomy, University College London, London, United Kingdom.

Also at Department of Physics, University of Cape Town, Cape Town, South Africa.

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at Manhattan College, New York, NY, United States.

Also at Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

Also at School of Physics, Shandong University, Shandong, China.

Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.

Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at California Institute of Technology, Pasadena, CA, United States.

Also at Institute of Physics, Jagiellonian University, Krakow, Poland.

Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.

Also at Nevis Laboratory, Columbia University, Irvington, NY, United States.

Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

Also at Department of Physics, Oxford University, Oxford, United Kingdom.

Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.

Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

* Deceased.