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The ATLAS Collaboration

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Keywords: exotics, $Z'$, ditau, resonance, search

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 ten additional neutral pions. The $\tau_{\text{had}}\tau_{\text{had}}$ (branching ratio, BR=42%), $\tau_\mu\tau_{\text{had}}$ (BR=23%), $\tau_\tau\tau_{\text{had}}$ (BR=23%) and $\tau_e\tau_\mu$ (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 $\tau_{\text{had}}\tau_{\text{had}}$ 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 $\tau_\mu\tau_{\text{had}}$ and $\tau_e\tau_\mu$ 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 $\tau_{\text{had}}$ 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 various models are simulated with the parton showering and hadronisation performed by HERWIG 6.520 [18] 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 $Z\gamma$ 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 TAUULA [23]. The choice of parton distribution functions (PDFs) depends on the generator: CTEQ6L1 [24] is used with ALPGEN, CT10 [25] with MC@NLO and MRST2007 LO* [26] with PYTHIA and AcerMC.

The $Z/\gamma^*$ 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 $Z/\gamma^*$+jets and $Z^0 \rightarrow \tau\tau$ 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 inner detector track with a track from the muon spectrometer. They are required to have $p_T > 10$ GeV and $|\eta| < 2.5^\dagger$. 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$^\ddagger$. In the $\tau_{\text{had}}$ 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

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

$^\ddagger$ Lepton isolation is defined using the sum of the $E_T$ deposited in calorimeter cells within $\Delta R < 0.2$ of the lepton, $E_T^{\text{iso}}$, 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 $E_T^{\text{iso}}/p_T < 4\%$ and $E_T^{\text{iso}}/p_T < 6\%$ in the $\tau_{\text{had}}$ channel. Isolated electrons must have $p_T^{\text{iso}}/p_T < 5\%$ and $E_T^{\text{iso}}/p_T < 5\%$ if $p_T < 100$ GeV or $E_T^{\text{iso}}/p_T < 5$ GeV otherwise ($E_T^{\text{iso}}/p_T < 6\%$ and $p_T^{\text{iso}}/p_T < 8\%$ in the $\tau_{\text{had}}$ channel).
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 $\tau_{\nu}$ channels and 60% (loose) for the $\tau_{\tau}$ 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, $|\eta| < 2.47$ (the EM calorimeter transition region is excluded). In the $\tau_{\nu}$ channels, tau candidates are required to have only one track, which must not be in the range $|\eta| < 0.05$, and to pass a muon veto. The removed pseudorapidity region corresponds to a gap in the transition radiation tracker that reduces the power of electron/pion discrimination. In the $\tau_{\tau}$ channel, tau candidates are also required to pass an electron veto using BDTs.

Geometric overlap of objects with $\Delta R < 0.2$ is resolved by selecting only one of the overlapping objects in the following order of priority: muons, electrons, tau candidates and jets. The missing transverse momentum (with magnitude $E_T^{\text{miss}}$) 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 $\tau_{\nu}$ 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 tau candidates in the transverse plane must be greater than 2.7 radians.

Selected events in the $\tau_{\nu}$ 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 $\tau_{\nu}$ channel, the $Z \rightarrow ee$ and multijet contributions are reduced to a negligible level by requiring $E_T^{\text{miss}} > 30$ GeV. The $W$+jets background is suppressed by requiring the transverse mass, $m_T$, of the electron-$E_T^{\text{miss}}$ system, defined as

$$m_T = \sqrt{2p_T E_T^{\text{miss}} (1 - \cos \Delta \phi)},$$

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

Selected events in the $\tau_{\nu}$ 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 $p_T^{\text{rel}} < 10$ GeV, with

$$p_T^{\text{rel}} = \hat{p}_T \cdot \hat{\zeta} + \hat{p}_{T\mu} \cdot \hat{\zeta},$$

where $\hat{\zeta}$ is a unit vector along the bisector of the $e$ and $\mu$ momenta. This selection provides good suppression of the diboson and $t\bar{t}$ backgrounds. For $Z'$ events, the $E_T^{\text{miss}}$ tends to point away from the highest-$p_T$ lepton, so the angle between the highest-$p_T$ lepton and $E_T^{\text{miss}}$ 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 $E_T^{\text{miss}}$, neglecting longitudinal momentum components and the tau lepton mass,

$$m_T^{\text{tot}} = \sqrt{2p_T1p_T2C + 2E_T^{\text{miss}}p_T1C_1 + 2E_T^{\text{miss}}p_T2C_2},$$

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 $E_T^{\text{miss}}$ 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 $\tau_{\nu}$ channel are multijet production and $Z/\gamma^* \rightarrow \tau\tau$. Minor
The dominant background processes in the $\tau\tau$ channel come from $Z/\gamma^* \rightarrow \tau\tau$, $W$+jets, $t\bar{t}$ 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 $\tau\tau$ channel come from $Z/\gamma^* \rightarrow \tau\tau$, $W$+jets, $t\bar{t}$ and diboson production. Contributions from processes such as $Z(\rightarrow \ell\ell)$+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 $\tau_{\tau \text{had}}$ 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 statistical uncertainty due to the choice of the fitting function in the high-mass tail is less than a percent of the total background in both the $\tau_{\text{had} \tau_{\text{had}}}$ channel and the transverse mass formed by the lepton and $E_T^{\text{miss}}$, $m_T(p_T, E_T^{\text{miss}})$, to be less than 30 GeV. For the $\tau_{\text{had} \tau_{\text{had}}}$ channel, where the multijet contribution is dominated by $b$-quark-initiated jets, the muon is additionally required to have a transverse impact parameter of $|d_0(\mu)| > 0.08$ 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. The $\tau_{\text{had} \tau_{\text{had}}}$ channel the anti-isolated sample includes all muons that fail isolation, while in the $\tau_{\text{had} \tau_{\text{had}}}$ 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 $\eta$:

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

Contamination from real isolated leptons is estimated using simulation and subtracted from $N_{\text{iso}}$ ($\sim 3\%$ for $\tau_{\text{had} \tau_{\text{had}}}$ and $\sim 25\%$ for $\tau_{\text{had} \tau_{\text{had}}}$). 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:

$$N_{\text{multijet}}(p_T, \eta, x) = f_{\text{iso}}(p_T, \eta) \times \left( N_{\text{data}}^{\text{anti-iso}}(p_T, \eta, x) - N_{\text{MC}}^{\text{anti-iso}}(p_T, \eta, x) \right).$$  (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, $N_{\text{anti-iso}}$, 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 $E_T^{\text{miss}}$ 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 $\tau_{\mu \tau_{\text{had}}}$ and $\tau_{\tau \tau_{\text{had}}}$ channels.

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; $E_T^{\text{miss}} < 15$ GeV for the $\tau_{\mu \tau_{\text{had}}}$ channel, $E_T^{\text{miss}} < 30$ GeV for the $\tau_{\tau \tau_{\text{had}}}$ channel; and the transverse mass formed by the lepton and $E_T^{\text{miss}}$, $m_T(p_T, E_T^{\text{miss}})$, to be less than 30 GeV. For the $\tau_{\mu \tau_{\text{had}}}$ channel, where the multijet contribution is dominated by $b$-quark-initiated jets, the muon is additionally required to have a transverse impact parameter of $|d_0(\mu)| > 0.08$ 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. The $\tau_{\text{lep} \tau_{\text{had}}}$ channel the anti-isolated sample includes all muons that fail isolation, while in the $\tau_{\text{lep} \tau_{\text{had}}}$ 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 $\eta$:

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

Contamination from real isolated leptons is estimated using simulation and subtracted from $N_{\text{iso}}$ ($\sim 3\%$ for $\tau_{\mu \tau_{\text{had}}}$ and $\sim 25\%$ for $\tau_{\tau \tau_{\text{had}}}$). 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:

$$N_{\text{multijet}}(p_T, \eta, x) = f_{\text{iso}}(p_T, \eta) \times \left( N_{\text{data}}^{\text{anti-iso}}(p_T, \eta, x) - N_{\text{MC}}^{\text{anti-iso}}(p_T, \eta, x) \right).$$  (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, $N_{\text{anti-iso}}$, 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 $E_T^{\text{miss}}$ 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 $\tau_{\mu \tau_{\text{had}}}$ and $\tau_{\tau \tau_{\text{had}}}$ channels.

5.3. $W$+jets background in the $\tau_{\text{lep} \tau_{\text{had}}}$ channels

The $W$+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+jets events. A high purity W+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 $m_T(ℓ, E_{T miss}^{\text{jet}})$ between 70 and 200 GeV. For the $τ_\tau$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, $N^{\text{pass}}_{\tau}$, divided by the number that fail, $N^{\text{fail}}_{\tau}$, binned in $p_T$ and $\eta$:

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

(7)

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

\[ N_{W+jets}(p_T, \eta, x) = f_\tau(p_T, \eta) \times \left( N^{\text{fail}}_{\text{data}}_{\tau}(p_T, \eta, x) - N^{\text{fail}}_{\text{MC}}_{\tau}(p_T, \eta, x) \right). \]  

(8)

The shape of the W+jets background is modelled using events in the data that failed the BDT ID, $N^{\text{fail}}_{\text{data}}_{\tau}$, with the multijet contamination, $N^{\text{fail}}_{\text{multijet}}_{\tau}$ (estimated from data), and other contamination, $N^{\text{fail}}_{\text{MC}}_{\tau}$ (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+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+jets events are not strongly correlated with the selection used to define the W+jets control region. This assumption has been verified by comparing the $m_T$ selection criterion used to define the W+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 $Z'/\gamma^* \to \tau\tau$ 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 CT10 and MSTW PDF sets. Additionally, for $Z'/\gamma^* \to \tau\tau$, 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 $W \to \tau\nu$ and $Z \to \tau\tau$ 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 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 $Z \to ee$ 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 $Z \to \tau\tau$ 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 \( E_T^{\text{miss}} \) calculation. The uncertainty on the \( E_T^{\text{miss}} \) 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 \( \tau \) hadronic channels. The fake factor estimate of the \( W + \text{jets} \) background in the \( \tau \) leptonic channels and from the statistical uncertainty of the MC samples in the \( \tau \tau \mu \mu \) channel. The dominant uncertainty on the signal for the \( \tau \) hadronic and \( \tau \) leptonic channels comes from the tau identification efficiency and for the \( \tau \tau \mu \mu \) channel, from the statistical uncertainty on the MC samples.

<table>
<thead>
<tr>
<th>Uncertainty [%]</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hh</td>
<td>µµ eµ µµ</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
<td>1 2 3</td>
<td>5 20 23 7</td>
</tr>
<tr>
<td>Eff. and fake rate</td>
<td>16 10 8 1</td>
<td>12 16 4 3</td>
</tr>
<tr>
<td>Energy scale and res.</td>
<td>5 7 6 2</td>
<td>-11 3 8 5</td>
</tr>
<tr>
<td>Theory cross section</td>
<td>8 6 6 5</td>
<td>9 4 4 5</td>
</tr>
<tr>
<td>Luminosity</td>
<td>4 4 4 4</td>
<td>2 2 2 4</td>
</tr>
<tr>
<td>Data-driven methods</td>
<td>- - - -</td>
<td>+2 1 6 16</td>
</tr>
</tbody>
</table>

Table 2: Uncertainties on the estimated signal and total background contributions in percent for each channel. The following signal masses, chosen to be close to the region where the limits are set, are used: 1250 GeV for \( \tau \) hadronic (hh); 1000 GeV for \( \tau \) leptonic (µµ) and \( \tau \) leptonic (eµ); and 750 GeV for \( \tau \tau \mu \mu \). A dash denotes that the uncertainty is not applicable. The statistical uncertainty corresponds to the uncertainty due to limited sample size in the MC and control regions.

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.

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 \( Z'_{\text{SSM}} \) 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 \( \tau \) hadronic; 1.07 and 1.06 TeV \( \tau \) leptonic; 1.10 and 1.03 TeV \( \tau \tau \mu \mu \); and 0.72 and 0.82 TeV \( \tau \tau \mu \mu \).

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 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 \( p\bar{p} \) collisions at \( \sqrt{s} = 7 \) TeV at the LHC. The \( \tau \) hadronic, \( \tau \mu \) hadronic, \( \tau \tau \mu \) and \( \tau \tau \mu \mu \) channels are analysed. The observed number of events in the high-transverse-mass region is consistent with the SM expectation. 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.

9. Acknowledgements

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Table 3: Number of expected and observed events after event selection for each analysis channel. The expected contribution from the signal and background in each channel is calculated for the signal mass point closest to the $Z'_{SSM}$ exclusion limit. The total uncertainties on each estimated contribution are shown. The signal efficiency denotes the expected number of signal events divided by the product of the production cross section, the ditau branching fraction and the integrated luminosity, $\sigma(pp \rightarrow Z'_{SSM}) \times BR(Z'_{SSM} \rightarrow \tau\tau) \times \int L dt$.

<table>
<thead>
<tr>
<th>$m_{Z'}$ [GeV]</th>
<th>$\tau_{\text{had}\tau_{\text{had}}}$</th>
<th>$\tau_{\mu\tau_{\text{had}}}$</th>
<th>$\tau_{e\tau_{\text{had}}}$</th>
<th>$\tau_{e\tau_{\mu}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1250</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>1000</td>
<td>0.80±0.22</td>
<td>0.8±0.4</td>
<td>0.33±0.10</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>0.01</td>
<td>&lt; 0.1</td>
<td>&lt; 0.01</td>
<td>0.06±0.02</td>
</tr>
<tr>
<td>400</td>
<td>0.02</td>
<td>0.33±0.15</td>
<td>0.13±0.09</td>
<td>0.97±0.22</td>
</tr>
<tr>
<td>350</td>
<td>0.01</td>
<td>0.23±0.07</td>
<td>0.06±0.03</td>
<td>1.69±0.24</td>
</tr>
<tr>
<td>300</td>
<td>0.01</td>
<td>0.19±0.18</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>250</td>
<td>0.24±0.15</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>200</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>

Observed limits

---

Figure 2: (a) The expected (dashed) and observed (solid) 95% credibility upper limits on the cross section times $\tau^+\tau^-$ branching fraction, in the $\tau_{\text{had}\tau_{\text{had}}}$, $\tau_{\mu\tau_{\text{had}}}$, $\tau_{e\tau_{\text{had}}}$ and $\tau_{e\tau_{\mu}}$ channels and for the combination. The expected $Z'_{SSM}$ 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. $Z'_{SSM}$ 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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References


Universidad Técnica Federico Santa María, Valparaiso, Chile
33 (a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b)Department of Modern Physics, University of Science and Technology of China, Anhui; (c)Department of Physics, Nanjing University, Jiangsu; (d)School of Physics, Shandong University, Shandong; (e)Physics Department, Shanghai Jiao Tong University, Shanghai, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington NY, United States of America
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 (a)INFN Gruppo Collegato di Cosenza; (b)Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
38 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
39 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas TX, United States of America
41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham NC, United States of America
46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a)INFN Sezione di Genova; (b)Dipartimento di Fisica, Università di Genova, Genova, Italy
51 (a)E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b)High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Gießen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c)ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 Department of Physics, Indiana University, Bloomington IN, United States of America
61 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
62 University of Iowa, Iowa City IA, United States of America
63 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
64 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
65 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
66 Graduate School of Science, Kobe University, Kobe, Japan
67 Faculty of Science, Kyoto University, Kyoto, Japan
68 Kyotou University of Education, Kyoto, Japan
69 Department of Physics, Kyushu University, Fukuoka, Japan
70 Instituto de Fisica La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 (a)INFN Sezione di Lecce; (b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
77 Department of Physics and Astronomy, University College London, London, United Kingdom
78 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
79 Fysiska institutionen, Lunds universitet, Lund, Sweden
80 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Faculty des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; Faculté des Sciences Semlalia, Université Cadi Ayyad, LPEHA-Marrakech; Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco

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

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

Department of Physics, University of Washington, Seattle WA, United States of America

Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

Department of Physics, Shinshu University, Nagano, Japan

Fachbereich Physik, Universität Siegen, Siegen, Germany

Department of Physics, Simon Fraser University, Burnaby BC, Canada

SLAC National Accelerator Laboratory, Stanford CA, United States of America

Department of Physics, University of Johannesburg, Johannesburg; 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 of America

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 of America

Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

INFN Gruppo Collegato di Udine; ICTP, Trieste; Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

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

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

Department of Physics, University of British Columbia, Vancouver BC, Canada

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

Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison WI, United States of America

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 of America

Yerevan Physics Institute, Yerevan, Armenia

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