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Search for heavy resonances decaying to tau lepton pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract: A search for heavy resonances that decay to tau lepton pairs is performed using proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$. The data were collected with the CMS detector at the CERN LHC and correspond to an integrated luminosity of $2.2\,\text{fb}^{-1}$. The observations are in agreement with standard model predictions. An upper limit at 95% confidence level on the product of the production cross section and branching fraction into tau lepton pairs is calculated as a function of the resonance mass. For the sequential standard model, the presence of Z' bosons decaying into tau lepton pairs is excluded for Z' masses below 2.1 TeV, extending previous limits for this final state. For the topcolor-assisted technicolor model, which predicts Z' bosons that preferentially couple to third-generation fermions, Z' masses below 1.7 TeV are excluded, representing the most stringent limit to date.

Keywords: Beyond Standard Model, Hadron-Hadron scattering (experiments), Particle and resonance production

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Contents

1 Introduction

The standard model (SM) of particle physics is a successful theory that can explain many experimental observations involving weak, electromagnetic, and strong interactions. Nevertheless, it cannot be an ultimate theory of nature since it fails, for instance, to provide an explanation for the mass of neutrinos and lacks a particle candidate for dark matter. Many models of physics beyond the SM have therefore been proposed. Such models often predict new heavy particles that could be observed at the CERN LHC.

A straightforward way to extend the SM gauge structure is to include an additional U(1) group with an associated neutral gauge boson, denoted Z'. The universality of couplings is not necessary for new gauge bosons. Indeed, models exist that incorporate generation-dependent couplings, resulting in Z' bosons that preferentially decay into fermions of the third generation [1, 2]. Such models motivate a search for Z' resonances that decay to a pair of τ leptons.

In particular, extensions to the SM proposed as an explanation for the high mass of the top quark predict Z' bosons that typically couple to third-generation fermions [2]. Examples are the topcolor-assisted technicolor (TAT) models [3, 4]. A widely used benchmark model in searches for Z' bosons is the sequential standard model (SSM) [5], which predicts a neutral spin-1 Z' boson, denoted Z'_{SSM}, with the same couplings to quarks and leptons as the SM Z boson.

Results of direct searches for heavy $\tau\tau$ resonances in proton-proton (pp) collisions at either $\sqrt{s} = 7$ or 8 TeV have been reported by the ATLAS and CMS Collaborations and exclude Z'_{SSM} masses below 2.0 TeV [6–8]. The most stringent mass limits on Z'_{SSM} production, set by ATLAS and CMS in searches for a narrow resonance decaying into an e^+e^- or $\mu^+\mu^-$ pair, are 3.4 [9] and 3.2 [10] TeV, respectively.

In this paper we report on a search for physics beyond the SM in events containing a pair of high transverse momentum (p_T) oppositely charged τ leptons. Four $\tau\tau$ final states, $\tau_e\tau_\mu$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, and $\tau_h\tau_h$, are selected, where τ_ℓ ($\ell = e, \mu$) and τ_h refer to the leptonic and hadronic decay modes of the τ lepton, respectively. The study is based on a data sample of pp collisions at $\sqrt{s} = 13$ TeV recorded with the CMS detector at the LHC. The sample corresponds to an integrated luminosity of 2.2 fb^{-1}.

2 The CMS experiment

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the inner tracker, the crystal electromagnetic calorimeter (ECAL), and the brass and scintillator hadron calorimeter (HCAL). The inner tracker is composed of a pixel detector and a silicon strip tracker, and measures charged-particle trajectories in the pseudorapidity range $|\eta| < 2.5$. The finely segmented ECAL consists of nearly 76 000 lead-tungstate crystals that provide coverage up to $|\eta| = 3.0$. The HCAL consists of a sampling calorimeter, which utilizes alternating layers of brass as an absorber and plastic scintillator as an active material, covering the range $|\eta| < 3$, and is extended to $|\eta| < 5$ by a forward hadron calorimeter. The muon system covers $|\eta| < 2.4$ and consists of four stations of gas-ionization muon detectors installed outside the solenoid and sandwiched between the layers of the steel return yoke. A detailed description of the CMS detector, together with a definition of the coordinate system and relevant kinematic variables, is given elsewhere [11].

Events of interest are selected using a two-tiered trigger system [12]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to less than 1 kHz before data storage.

3 Object reconstruction and identification

A particle-flow (PF) algorithm [13, 14] is used to combine information from all CMS subdetectors in order to reconstruct and identify individual particles in the event: muons, electrons, photons, and charged and neutral hadrons. The resulting set of particles is used to reconstruct the τ_h candidates, jets, missing transverse momentum, and the isolation variables described below. The primary vertex of an event is chosen to be the reconstructed vertex with the largest p_T^2 sum of associated tracks.

The τ_e and τ_μ are reconstructed and identified with the usual techniques for electrons and muons. Electrons are reconstructed as energy deposits in the ECAL associated with tracks in the tracking detector [10, 15]. Requirements on energy deposits in the calorimeter and on the number of hits in the inner tracker are imposed to distinguish electrons produced in hard scattering processes from charged pions and from electrons produced through photon conversions.

Muons are reconstructed using the inner tracker and the muon detectors [16, 17]. Quality requirements, based on the minimum number of hits in the inner tracker and muon detectors, are applied to suppress backgrounds from the decays-in-flight of light-flavor hadrons, and from hadron shower remnants that reach the muon system.

Both the electron and muon selections impose an isolation requirement to suppress both jets erroneously identified as leptons and genuine leptons from hadron decays. The isolation criterion for light leptons is based on the variable I_ℓ, which is the scalar p_T sum, divided by the lepton p_T, of charged and neutral PF candidates within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the lepton direction at the interaction vertex, where ϕ is the azimuthal angle. The sum excludes the lepton under consideration as well as charged particles from additional pp interactions within the same or a nearby bunch crossing ("pileup"). The contribution of neutral particles from pileup is accounted for by subtracting from the isolation sum a term given by the scalar p_T sum of charged hadrons from pileup vertices that appear within the isolation cone, multiplied by a factor of 0.5 to account for the ratio of neutral to charged hadron production. The isolation criterion is $I_\ell < 0.15$.

The τ_h candidates are reconstructed using the hadrons-plus-strips algorithm [18, 19], which is designed to optimize the performance of τ_h reconstruction and identification by considering specific τ lepton decay modes. Individual hadronic τ decay modes are reconstructed separately. The signatures distinguished by the algorithm are: a single charged hadron, a charged hadron plus up to two neutral pions, and three charged hadrons. Reconstructed τ_h leptons are required to be isolated to reduce background from misidentified light-quark or gluon jets. The isolation criterion for τ_h leptons is based on the scalar p_T sum S_τ of charged and neutral PF candidates within a cone of radius $\Delta R = 0.5$ around the τ_h direction, excluding the τ_h candidate and charged tracks from pileup. The contribution of neutral particles from pileup is accounted for by subtracting from S_τ the scalar p_T sum of charged particles from pileup interactions that appear within a cone of radius $\Delta R = 0.8$ around the τ_h candidate, multiplied by a factor of 0.2 [19]. The factor of 0.2 is chosen to render the τ_h identification efficiency insensitive to the level of pileup. The isolation criterion is $S_\tau < 0.8\,\text{GeV}$. The τ_h candidates are further distinguished from electrons and muons using dedicated algorithms, referred to as discriminators. The algorithm to discriminate a τ_h lepton from an electron utilizes observables that quantify the compactness and shape of energy deposits in the ECAL, to distinguish electromagnetic from hadronic showers, in combination with observables that are sensitive to the amount of bremsstrahlung radiation emitted along the highest p_T track of the τ_h candidate, and observables that are sensitive to the overall particle multiplicity. The discriminator against muons requires that no hits in the muon system be matched to the τ_h candidate. For a τ_h with $p_T > 20\,\text{GeV}$ and $|\eta| < 2.1$, the identification efficiency is approximately 55%. The probability for a

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light-quark or gluon jet, electron, and muon to be misidentified as a τ_{h} is approximately 1%, 0.2%, and 0.03%.

The jets are reconstructed using the anti-k_{T} jet algorithm [20, 21] with a distance parameter of 0.4. In order to tag jets from b quark decays, the combined secondary vertex (CSVv2) algorithm at the loose working point is used [22, 23]. This algorithm is based on the reconstruction of secondary vertices, together with track-based lifetime information. For b quark jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$, the identification efficiency is approximately 85%, while the probability for a light-quark or gluon (charm quark) jet to be misidentified as a b quark jet is approximately 10% (20%).

The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is defined as the negative of the vector sum of transverse momenta of all PF candidates reconstructed in the event. The magnitude of this vector is referred to as $E_{\mathrm{T}}^{\mathrm{miss}}$. The raw $E_{\mathrm{T}}^{\mathrm{miss}}$ value is modified to account for corrections to the energy scale of all the reconstructed jets in the event [24]. Events that contain large values of $E_{\mathrm{T}}^{\mathrm{miss}}$ as a consequence of instrumental effects, such as calorimeter noise, beam halo, or jets near nonfunctioning channels in the calorimeters, are removed from the analysis.

4 Signal and background Monte Carlo samples

The most important sources of background arise from the production of Drell-Yan events ($\mathrm{Z}/\gamma^* \to \tau^+\tau^-$), W bosons in association with one or more jets (W+jets), top quark pairs ($\mathrm{t\bar{t}}$), quantum chromodynamics (QCD) multijet events, and diboson events (WW, WZ, ZZ). Although the Drell-Yan background peaks around the Z pole mass, its tail extends into the high-mass region where a signal might be present. The W+jets events are characterized by an isolated lepton from the decay of the W boson and an uncorrelated jet misidentified as a light lepton or τ_{h} lepton. Background from $\mathrm{t\bar{t}}$ events contains one or two b quark jets, in addition to isolated τ_ℓ or τ_{h} candidates. Background from diboson events produces isolated leptons if the gauge bosons decay leptonically. Should the gauge bosons decay hadronically, one of the jets may be misidentified as a τ_{h} lepton. Finally, QCD multijet background is characterized by jets with low charged-track multiplicity that can be misidentified as τ_ℓ or τ_{h} candidates.

Monte Carlo (MC) event generators are used to simulate the signal and SM backgrounds. The Drell-Yan, W+jets, and $\mathrm{t\bar{t}}$ processes are generated with the MadGraph5_aMC@NLO program [25]. The PYTHIA 8.2 program is used to generate the diboson and signal events [26]. The signal events are generated with Z′ masses ranging from 0.5 to 3.0 TeV, with a step size of 0.5 TeV. The expected signal yields are rescaled to next-to-leading order (NLO) accuracy using a K-factor of 1.3 [10]. The electroweak NLO corrections are small in the range of masses considered. The SM samples are normalized using the most accurate cross section calculations currently available [25, 27–37], generally with NLO or next-to-next-leading order (NNLO) accuracy. The NNPDF 3.0 [38] parton distribution functions (PDF) are used, and all simulated samples use the PYTHIA program with the CUETP8M1 tune [39] to describe parton showering and hadronization. The simulation of pileup is performed by superimposing minimum bias interactions onto the hard scattering process, matching the pileup profile in data. The mean number of interactions in a single bunch crossing in the analysed data set is approximately 14. The MC-generated events are propagated through a Geant4-based simulation [40] of the CMS apparatus.

5 Event selection

The requirements described below define the signal region. A new heavy neutral gauge boson decaying into a τ lepton pair would be characterized by an excess above the SM expectation for the rate of events with two high-p_{T}, oppositely charged, isolated τ lepton candidates. Single-lepton triggers are used to select $\tau_{\mathrm{e}}\tau_{\mu}$, $\tau_{\mathrm{e}}\tau_{\mathrm{h}}$, and $\tau_{\mu}\tau_{\mathrm{h}}$ events, while a trigger requiring at least two τ_{h} candidates at the L1 and HLT levels is used to select $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ events. The triggers are designed to allow the use of the background estimation methods outlined in section 6. Electrons (muons) are required to have $p_{\mathrm{T}} > 35\,(30)\,\mathrm{GeV}$. The τ_{h} candidates are required to have $p_{\mathrm{T}} > 20$ and $60\,\mathrm{GeV}$ in the $\tau_{\ell}\tau_{\mathrm{h}}$ and $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ channels, respectively. The τ lepton candidate p_{T} is defined by the vector p_{T} sum of its visible decay products. Both τ_{ℓ} and τ_{h} candidates must have $|\eta| < 2.1$ and satisfy isolation requirements to mitigate background from misidentified jets. The p_{T} thresholds on the τ_{e}, τ_{μ}, and τ_{h} candidates are chosen such that the trigger efficiency is about 90% or higher in each channel considered.

The $\tau\tau$ pairs are formed from oppositely charged candidates with $\Delta R(\tau_1, \tau_2) > 0.5$. The τ_{h} charge is reconstructed from the sum of the charges of the associated tracks used to reconstruct the decay mode and is required to be ± 1. Owing to the large invariant mass of the $\tau\tau$ resonances assumed for this study, the two τ candidates are expected to be back-to-back. Events are therefore required to satisfy $\cos\Delta\phi(\tau_1, \tau_2) < -0.95$. An additional requirement of $E_{\mathrm{T}}^{\mathrm{miss}} > 30\,\mathrm{GeV}$ is applied to preferentially select events with neutrinos from the τ lepton decays rather than apparent $E_{\mathrm{T}}^{\mathrm{miss}}$ due to mismeasurement of jet p_{T}. The signal efficiency of this requirement is 85% efficiency or more, depending on the Z' boson mass.

The direction of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is required to be consistent with the expectation for a pair of high-p_{T} τ lepton decays, to reduce the background from events with W bosons (primarily W+jets and $\mathrm{t\bar{t}}$ events). This requirement is implemented through a variable known as "CDF-ζ" [41], referred to below as the ζ variable. This variable is defined by considering a unit vector, denoted the $\hat{\zeta}$ axis, along the bisector between the p_{T} directions of the two τ lepton candidates. Two projection variables for the visible τ lepton decay products and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ are then constructed: $p_{\zeta}^{\mathrm{vis.}} = (\vec{p}_{\mathrm{T}}^{\tau_1} + \vec{p}_{\mathrm{T}}^{\tau_2}) \cdot \hat{\zeta}$ and $p_{\zeta} = (\vec{p}_{\mathrm{T}}^{\tau_1} + \vec{p}_{\mathrm{T}}^{\tau_2} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) \cdot \hat{\zeta}$. In contrast to signal events in which $p_{\zeta}^{\mathrm{vis.}}$ and p_{ζ} are strongly correlated, these two variables are nearly independent in events with a W boson because in this case the direction and magnitude of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ are correlated with those of the lepton, but not with those of the jet. Events are selected by requiring $\zeta = p_{\zeta} - 3.1 p_{\zeta}^{\mathrm{vis.}} > -50\,\mathrm{GeV}$. Residual contributions from $\mathrm{t\bar{t}}$ events are reduced by selecting events without a tagged b jet.

To distinguish more effectively between signal and background events, the visible τ lepton energies and momenta E_{τ_i} and $\vec{p}_{\tau_i}$ (with $i = 1, 2$), along with $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, are used to reconstruct a mass value m, defined as

$$m(\tau_1, \tau_2, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) = \sqrt{(E_{\tau_1} + E_{\tau_2} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\tau_1} + \vec{p}_{\tau_2} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}})^2}. \tag{5.1}$$

We do not apply a selection requirement on the mass variable of eq. (5.1), but instead utilize it to search for a broad enhancement in the $m(\tau_1, \tau_2, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})$ distribution consistent with new physics.

The product of signal acceptance and efficiency for $\mathrm{Z}' \to \tau\tau$ events varies with the Z' boson mass. The $\tau_\mu\tau_\mathrm{h}$ and $\tau_\mathrm{h}\tau_\mathrm{h}$ channels provide the largest product of acceptance and efficiency, while the $\tau_\mathrm{e}\tau_\mu$ channel has the lowest. For the combination of all four channels the product of acceptance and efficiency amounts to 6.3, 13, and 14%, respectively, for $m\,(\mathrm{Z}'_{\mathrm{SSM}}) = 0.5$, 1.5, and 3.0 TeV.

6 Background estimation

To estimate the background contributions in the signal region, techniques based on data control regions are employed wherever possible. The strategy when using such a technique is to modify the standard event selection requirements in order to define samples enriched with events from specific sources of background. These control regions are used to model the $m(\tau_1, \tau_2, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})$ shape of the backgrounds and to measure the probability for an event to satisfy the selection requirements. Contributions from additional background sources in a given control region are subtracted using their predictions from simulation. The background estimation methods based on data control regions are validated by determining the ability of the method, applied to simulated samples, to predict correctly the true number of background events and the shape of the $m(\tau_1, \tau_2, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})$ distribution. In some cases, for backgrounds with misidentified leptons, the background estimation methods are also validated with the data. In such tests, the agreement between the relevant quantities is always within the statistical uncertainties, and is at the level of 20% or better, depending on the channel. In cases where an approach based on a data control region is not possible, or for backgrounds with small expected contributions, we rely on simulation. For the most relevant SM contributions evaluated from simulation, we verify that the MC prediction is in agreement with the data in background-enhanced regions.

The QCD multijet background is relevant for both the $\tau_\mathrm{h}\tau_\mathrm{h}$ and $\tau_\ell\tau_\mathrm{h}$ channels, where it represents more than 80% or 20% of the total background, respectively. The contribution from QCD multijet events in the $\tau_\mathrm{e}\tau_\mu$ channel is approximately 5% ($< 1\%$) for $m(\tau_1, \tau_2, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) > 85\,(300)$ GeV. In the $\tau_\mathrm{h}\tau_\mathrm{h}$ final state, this background is evaluated from the like-sign $\tau\tau$ mass distribution ($> 98\%$ purity of QCD multijet events), which is scaled using the opposite-sign-to-like-sign ratio measured in a control region where the $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement is inverted ($E_{\mathrm{T}}^{\mathrm{miss}} < 30$ GeV). In the $\tau_\mathrm{e}\tau_\mathrm{h}$ final state, the QCD multijet background is evaluated using the mass shape reconstructed from a data sample with a nonisolated τ_h. This mass shape is weighted by the probability for a jet to satisfy the τ_h isolation criterion, which is measured from a sample of like-sign $\tau\tau$ candidates. The systematic uncertainties in these estimates are discussed in section 7.

Background from W+jets events is important in the $\tau_\ell\tau_\mathrm{h}$ channels, representing about 40 (45)% of the total background when ℓ is an electron (muon). The contribution from W+jets events in the $\tau_\mathrm{e}\tau_\mu$ and $\tau_\mathrm{h}\tau_\mathrm{h}$ channels is <1% for $m(\tau_1, \tau_2, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) > 300$ GeV. To estimate this background, we take the mass distribution of events selected in data with one nonisolated τ_h, subtract the QCD multijet background as determined from a data control region, subtract other backgrounds as determined from simulation, and weight the distribution by the probability for a jet to satisfy the τ_h isolation criterion. This probability is measured in a data control region for which the ζ and $\cos\Delta\phi(\tau_1, \tau_2)$ requirements are inverted ($\zeta < -50\,\text{GeV}$ or $\cos\Delta\phi > -0.95$). The sample used to determine the QCD multijet contribution to the W+jets control region contains a small expected contribution from W+jets events, which is subtracted using simulation. The systematic uncertainties in these estimates are discussed in section 7.

The $\text{t}\bar{\text{t}}$ background is relevant for the $\tau_e\tau_\mu$ channel, where it represents more than 30% (70%) of the total background for $m(\tau_1, \tau_2, \vec{p}_T^{\,\text{miss}}) > 85\,(300)\,\text{GeV}$. Its contribution to the other channels is $<2\%\,(<15\%)$ for $m(\tau_1, \tau_2, \vec{p}_T^{\,\text{miss}}) > 85\,(300)\,\text{GeV}$. High-purity samples of $\text{t}\bar{\text{t}}$ events are obtained by requiring the presence of at least one b-tagged jet with $p_T > 20\,\text{GeV}$. The $\text{t}\bar{\text{t}}$ prediction from simulation agrees with the observed yield and mass shape in the control sample, with a statistical uncertainty of ∼8% in the ratio of the simulated to the observed yield. Thus the $\text{t}\bar{\text{t}}$ prediction in the signal region is based on simulation with an additional systematic uncertainty of 8%.

The SM Drell-Yan background contributes to all final states, ranging from about 10% of the total background in the $\tau_h\tau_h$ channel to 40% in the other channels. It is estimated from simulation, after comparing the expectations from simulation with data in low-mass control regions where no signal is expected [6], specifically regions where $E_T^{\text{miss}} < 30\,\text{GeV}$, and either $m(\tau_1, \tau_2) < 100\,\text{GeV}$ ($\tau_h\tau_h$ channel) or $m(\tau_1, \tau_2, \vec{p}_T^{\,\text{miss}}) < 200\,\text{GeV}$ (the other channels). The data and simulation are found to be in agreement within the systematic uncertainties discussed in section 7.

The remaining backgrounds described in section 4 are estimated using simulation.

7 Systematic uncertainties

The main source of systematic uncertainty is the uncertainty in the estimation of the background, due to the limited number of events in the data control regions. This results in uncertainties ranging from 8% for the contribution from dominant backgrounds such as that from W+jets events in the $\tau_\ell\tau_h$ channels, to 68% for the small contribution of QCD multijet events in the $\tau_\mu\tau_h$ channel. Nondominant backgrounds in the control regions, including the resulting uncertainties in the control sample purities, make a minor contribution to the overall systematic uncertainty.

The efficiencies for electron and muon reconstruction, identification, and triggering have an uncertainty of approximately 2%, measured using $\text{Z} \to \ell^+\ell^-$ events [15, 17]. For the uncertainty in the description by the simulation of the identification efficiency for high-p_T electrons (muons), an uncertainty of 6% (7%), independent of p_T, is assigned, as described in ref. [10]. The systematic uncertainty on τ_h trigger efficiency is 5% per τ_h candidate, as measured with $\text{Z} \to \tau_\mu\tau_h$ events triggered by single-muon triggers. Systematic effects associated with τ_h identification are measured using the visible $\tau\tau$ mass distribution around the Z boson peak as well as off-mass-shell virtual W bosons selected with a single τ_h candidate and large E_T^{miss} [19]. The resulting uncertainty is 6% per τ_h candidate. An additional systematic uncertainty, which dominates for high-p_T τ_h candidates, is related to the confidence that the MC simulation correctly models the identification efficiency, and is validated with high-p_T jet and electron candidates that produce τ_h-like signatures in the detector. This additional uncertainty increases linearly with p_T and amounts to 20% per τ_h candidate at $p_\mathrm{T} = 1\,\mathrm{TeV}$ (correlated between both candidates in the $\tau_\mathrm{h}\tau_\mathrm{h}$ channel), resulting in an uncertainty of 4% (10%) for a reconstructed mass of 0.5 TeV in the $\tau_\ell\tau_\mathrm{h}$ ($\tau_\mathrm{h}\tau_\mathrm{h}$) channel, and 12% (25%) for a mass of 2 TeV. The uncertainty in the integrated luminosity measurement is 2.7% [42]. Uncertainties that affect the $m(\tau_1, \tau_2, \vec{p}_\mathrm{T}^\mathrm{\,miss})$ mass shape include the electron, muon, and τ_h energy scales, and the jet and $E_\mathrm{T}^\mathrm{miss}$ energy scales and resolutions. The uncertainty in the probability for a light quark or gluon jet to be misidentified as a b quark jet (20%) is also considered, and has a ∼3% effect on the signal acceptance and a negligible effect on the $m(\tau_1, \tau_2, \vec{p}_\mathrm{T}^\mathrm{\,miss})$ mass shape. The uncertainty in the signal acceptance associated with the PDFs is evaluated in accordance with the PDF4LHC recommendations [43] and amounts to a few percent.

The systematic uncertainties in the W+jets, Drell-Yan, QCD multijet, and $\mathrm{t\bar{t}}$ background normalizations are approximately 9% (9%), 10% (19%), 68% (20%), and 8% (8%), respectively, in the $\tau_\ell\tau_\mathrm{h}$ ($\tau_\mathrm{h}\tau_\mathrm{h}$) channel. The total systematic uncertainty in the SM background yield ranges from <10% at low mass in the $\tau_\ell\tau_\mathrm{h}$ channels to ∼100% at high mass in the $\tau_\mathrm{h}\tau_\mathrm{h}$ channel. The normalization uncertainties have a fully correlated effect across all mass bins, while the shape uncertainties account for systematic migrations of expected yields among neighboring bins in $m(\tau_1, \tau_2, \vec{p}_\mathrm{T}^\mathrm{\,miss})$.

8 Results

The upper section of table 1 lists the estimated background yields and the total number of observed events for each channel, integrated over all values of reconstructed mass. The lower section of table 1 lists the results for $m(\tau_1, \tau_2, \vec{p}_\mathrm{T}^\mathrm{\,miss}) > 300\,\mathrm{GeV}$, where the signal is primarily expected. The distributions of $m(\tau_1, \tau_2, \vec{p}_\mathrm{T}^\mathrm{\,miss})$ are shown in figure 1 for all four channels.

The observed mass spectra shown in figure 1 do not reveal evidence for new particles decaying to τ lepton pairs. We proceed to set upper limits on the product of the signal cross section and the branching fraction for a $\mathrm{Z'}$ boson decaying to a τ lepton pair. The modified frequentist construction $\mathrm{CL_s}$ [44–46] is used to determine these upper limits at 95% confidence level (CL) as a function of the $\mathrm{Z'}$ mass for each $\tau\tau$ final state. For each decay channel, and for each bin of reconstructed mass above 85 GeV, the observed number of events is fitted by a Poisson distribution whose mean is the sum of the total SM expectation, determined as described in section 6, and a potential signal contribution determined from simulation. Systematic uncertainties are implemented as nuisance parameters, which are profiled, and modeled with gamma or log-normal priors for normalization parameters and Gaussian priors for shape uncertainties.

Figure 2 shows the observed and expected limits on the product of the cross section and the branching fraction for the decays into τ lepton pairs as functions of the $\mathrm{Z'}$ mass, together with the theoretical predictions from the SSM and TAT models. The shaded bands represent one and two standard deviation uncertainty intervals in the expected

Process	$\tau_e\tau_\mu$	$\tau_e\tau_h$	$\tau_\mu\tau_h$	$\tau_h\tau_h$
Drell-Yan	321 ± 37	375 ± 40	882 ± 130	8 ± 3
W+jets	19 ± 6	456 ± 35	916 ± 96	0.1 ± 0.1
Diboson	108 ± 11	18 ± 4	29 ± 7	0.5 ± 0.5
$t\bar{t}$	223 ± 20	26 ± 6	26 ± 7	—
QCD multijet	36 ± 16	250 ± 50	122 ± 84	49 ± 13
Total	707 ± 47	1125 ± 73	1976 ± 180	58 ± 13
Observed	728	1113	1807	55
Z'_{SSM} (1.0 TeV)	24.7 ± 1.9	19.1 ± 1.4	53 ± 4	45 ± 3
Z'_{SSM} (1.5 TeV)	4.7 ± 0.3	3.0 ± 0.1	9.4 ± 0.4	8.6 ± 0.4
Z'_{SSM} (2.0 TeV)	1.2 ± 0.1	0.77 ± 0.04	2.3 ± 0.1	2.1 ± 0.1

Process	$\tau_e\tau_\mu$	$\tau_e\tau_h$	$\tau_\mu\tau_h$	$\tau_h\tau_h$
Drell-Yan	4 ± 3	9 ± 4	16 ± 4	5 ± 2
W+jets	0.2 ± 0.5	7 ± 5	23 ± 9	0.004 ± 0.004
Diboson	23 ± 5	3 ± 2	6 ± 3	0.02 ± 0.02
$t\bar{t}$	65 ± 12	5 ± 3	4 ± 2	—
QCD multijet	0.8 ± 1.0	9 ± 3	4 ± 3	18 ± 6
Total	93 ± 13	33 ± 8	51 ± 11	23 ± 6
Observed	96	40	42	20
Z'_{SSM} (1.0 TeV)	21.1 ± 1.6	18.1 ± 1.3	49 ± 4	44 ± 3
Z'_{SSM} (1.5 TeV)	4.4 ± 0.3	2.9 ± 0.1	9.0 ± 0.4	8.5 ± 0.4
Z'_{SSM} (2.0 TeV)	1.2 ± 0.1	0.77 ± 0.04	2.3 ± 0.1	2.1 ± 0.1

Table 1. Numbers of events observed in data compared to the expected background yields and to the predicted numbers of signal events for Z'_{SSM} masses of 1.0, 1.5, and 2.0 TeV. The upper section of the table presents the inclusive yields. The lower section presents the yields after the requirement $m(\tau_1, \tau_2, \vec{p}_T^{\,miss}) > 300$ GeV. The uncertainties quoted in the background yields represent the combined statistical and systematic uncertainties.

limits obtained using a large sample of pseudo-experiments where the pseudodata are generated from distributions corresponding to the background-only hypothesis. The upper limit on the cross section times branching fraction $\sigma(pp \to Z')\,\mathcal{B}(Z' \to \tau\tau)$ corresponds to the point where the observed limit crosses the theory curve. In the TAT model the gauge group structure is characterized by a reduced coupling to light fermions (1st and 2nd generations) and an enhanced coupling to heavy fermions (3rd generation). Because light quark annihilation (e.g. $u\bar{u} \to Z'$) is the dominant Z' production mechanism at the LHC, the cross section $\sigma(pp \to Z')$ in the TAT model is suppressed (relative to that in the SSM model) because of the reduced coupling to light quarks. On the other hand, the

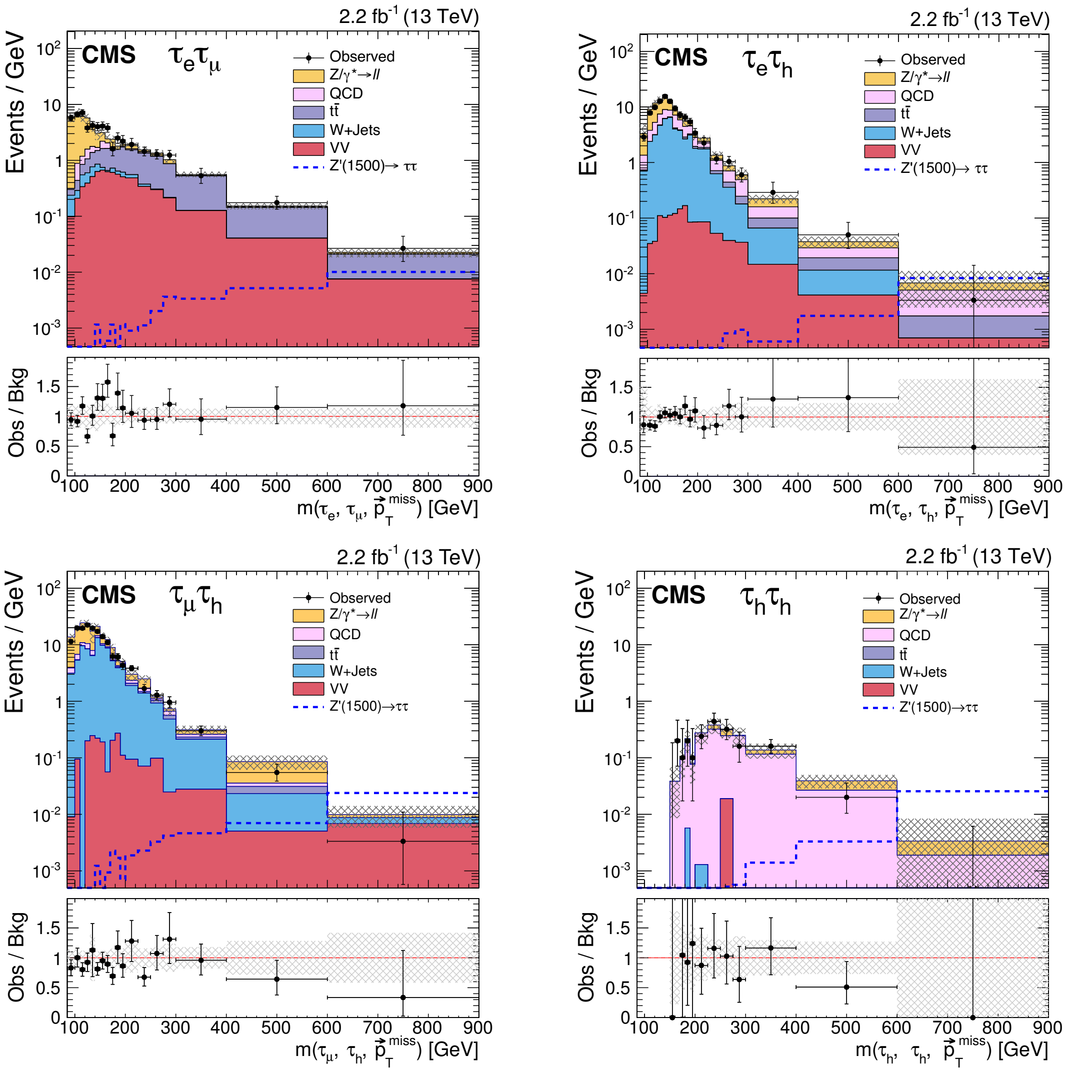

Figure 1. Observed $m(\tau_1, \tau_2, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})$ distribution in the signal region compared to the expected SM backgrounds for the (top left) $\tau_{\mathrm{e}}\tau_\mu$, (top right) $\tau_{\mathrm{e}}\tau_{\mathrm{h}}$, (bottom left) $\tau_\mu\tau_{\mathrm{h}}$, and (bottom right) $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ channels. The dashed histogram shows the distribution expected for a $\mathrm{Z}'_{\mathrm{SSM}}$ boson with mass 1500 GeV. The rightmost bins also include events with $m(\tau_1, \tau_2, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) > 900\,\mathrm{GeV}$, and are normalized to the displayed bin width. The lower panel shows the ratio of the observed number of events to the total background prediction. The shaded bands represent the total uncertainty in the background prediction.

branching fraction $\mathcal{B}(\mathrm{Z}' \to \tau\tau)$ in the TAT model is enhanced as a result of the stronger coupling to τ leptons. With the TAT parameters in refs. [3, 4], the suppression in the cross section outweighs the increase of the branching fraction. Overall, the product of the cross section and branching fraction $\sigma(\mathrm{pp} \to \mathrm{Z}')\,\mathcal{B}(\mathrm{Z}' \to \tau\tau)$ in the TAT model is approximately one-third of the value in the SSM model. Combining the four final states, we exclude $\mathrm{Z}'_{\mathrm{SSM}}$ and $\mathrm{Z}'_{\mathrm{TAT}}$ models with masses less than 2.1 TeV (1.9 TeV expected) and 1.7 TeV (1.5 TeV expected), respectively, at 95% CL.

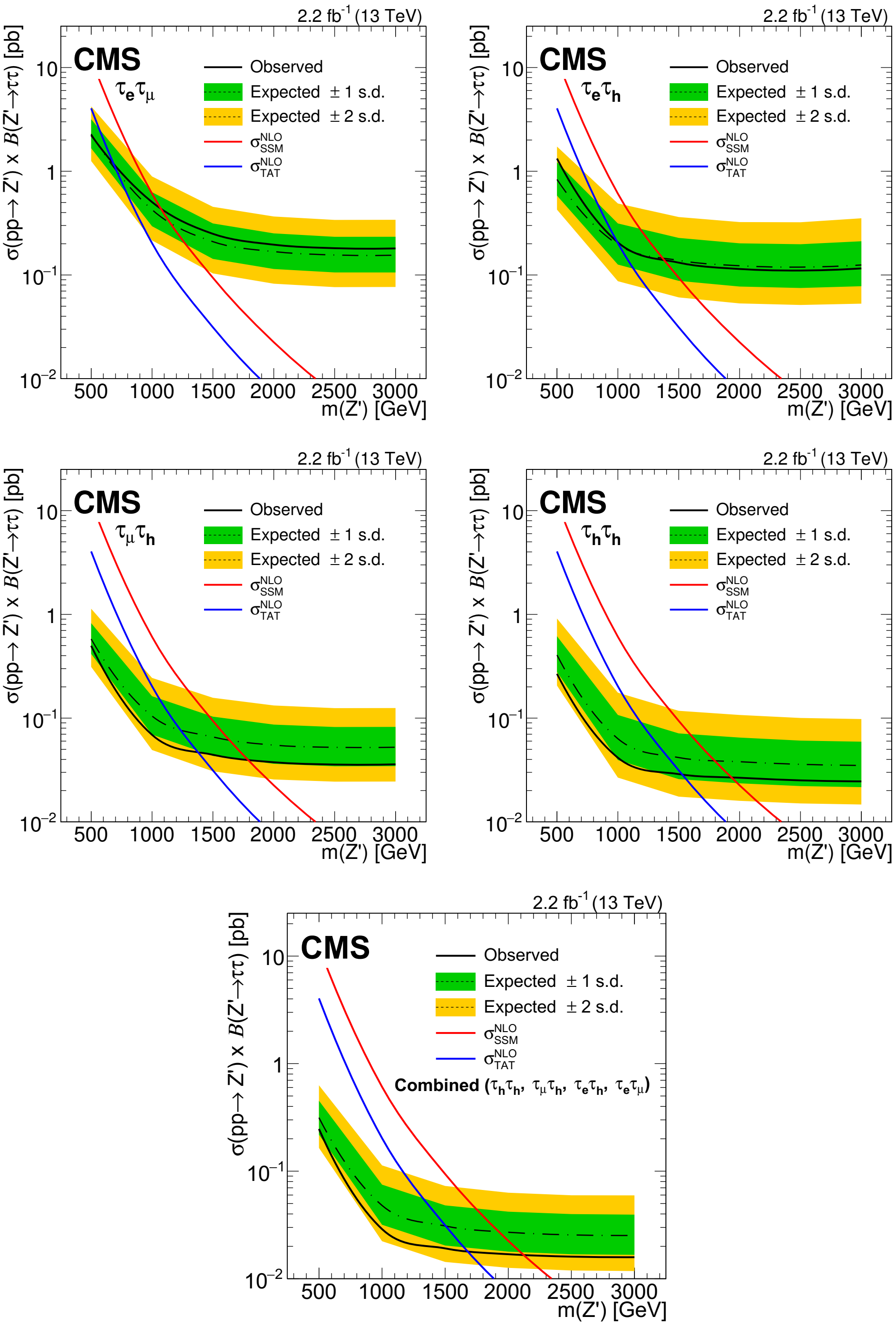

Figure 2. The observed 95% CL upper limits on the product of the cross section and branching fraction into τ lepton pairs as a function of the Z$'$ mass $m(\mathrm{Z}')$ (solid black lines), for the (top left) $\tau_e\tau_\mu$, (top right) $\tau_e\tau_h$, (middle left) $\tau_\mu\tau_h$, and (middle right) $\tau_h\tau_h$ final states, and (bottom) for the combination of the four channels. The expected limits (dash-dotted lines) with one and two standard deviation (s.d.) uncertainty bands are also shown. The predictions of the NLO theory cross sections in the SSM and TAT models are represented by the red (lighter) and blue (darker) solid curves, respectively.

9 Summary

A search for heavy resonances decaying to a tau lepton pair has been performed by the CMS experiment, using a data sample of proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ collected in 2015, corresponding to an integrated luminosity of $2.2\,\text{fb}^{-1}$. The tau leptons are reconstructed in their decays to an electron (τ_e) and muon (τ_μ), and in their hadronic decays (τ_h). The observed invariant mass spectra in the $\tau_\mu\tau_\text{h}$, $\tau_\text{e}\tau_\text{h}$, $\tau_\text{h}\tau_\text{h}$, and $\tau_\text{e}\tau_\mu$ channels are measured and are found to be consistent with expectations from the standard model. Upper limits at 95% confidence level are derived for the product of the cross section and branching fraction for a Z' boson decaying to a tau lepton pair, as a function of the Z' mass. The presence of Z' bosons decaying to a tau lepton pair is excluded for Z' masses below 2.1 TeV in the sequential standard model. This is the first search for heavy resonances decaying to a tau lepton pair using events from proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$, already extending previous limits [6–8] for this final state using the data sample collected in 2015. In the topcolor-assisted technicolor model, which predicts Z' bosons that exhibit enhanced couplings to third-generation fermions, the presence of Z' bosons decaying to a tau lepton pair is excluded for Z' masses below 1.7 TeV, resulting in the most stringent limit to date.

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37: Also at Institute for Nuclear Research, Moscow, Russia
38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
40: Also at University of Florida, Gainesville, U.S.A.
41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
42: Also at California Institute of Technology, Pasadena, U.S.A.
43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
45: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy

46: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
47: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
48: Also at National and Kapodistrian University of Athens, Athens, Greece
49: Also at Riga Technical University, Riga, Latvia
50: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
51: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
52: Also at Mersin University, Mersin, Turkey
53: Also at Cag University, Mersin, Turkey
54: Also at Piri Reis University, Istanbul, Turkey
55: Also at Gaziosmanpasa University, Tokat, Turkey
56: Also at Adiyaman University, Adiyaman, Turkey
57: Also at Ozyegin University, Istanbul, Turkey
58: Also at Izmir Institute of Technology, Izmir, Turkey
59: Also at Marmara University, Istanbul, Turkey
60: Also at Kafkas University, Kars, Turkey
61: Also at Istanbul Bilgi University, Istanbul, Turkey
62: Also at Yildiz Technical University, Istanbul, Turkey
63: Also at Hacettepe University, Ankara, Turkey
64: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
65: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
66: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
67: Also at Utah Valley University, Orem, U.S.A.
68: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
69: Also at Argonne National Laboratory, Argonne, U.S.A.
70: Also at Erzincan University, Erzincan, Turkey
71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
72: Now at The Catholic University of America, Washington, U.S.A.
73: Also at Texas A&M University at Qatar, Doha, Qatar
74: Also at Kyungpook National University, Daegu, Korea