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

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Abstract

A search for heavy neutral gauge bosons (Z') decaying into a pair of tau leptons is performed in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ at the CERN LHC. The data were collected with the CMS detector and correspond to an integrated luminosity of $138\,\text{fb}^{-1}$. The observations are found to be in agreement with the expectation from standard model processes. Limits at 95% confidence level are set on the product of the Z' production cross section and its branching fraction to tau lepton pairs for a range of Z' boson masses. For a narrow resonance in the sequential standard model scenario, a Z' boson with a mass below 3.5 TeV is excluded. This is the most stringent limit to date from this type of search.

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1 Introduction

The CMS experiment [1] at the CERN LHC is conducting an extensive program of searches for evidence of new particles predicted by various extensions of the standard model (SM). One of the simplest extensions postulates an additional $U(1)$ symmetry group that gives rise to the production of a new neutral gauge particle, analogous to the Z boson in the SM, commonly referred to as a Z′ boson. There are other more complicated extensions of the SM that also predict the existence of similar mediators, such as grand unified theories [2], $E(6)$ models [3], and the Randall–Sundrum model [4]. Searches for Z′ bosons have been carried out by the ATLAS and CMS Collaborations, placing stringent bounds on Z′ boson production as a function of its mass, $m_{Z'}$, especially for the $Z' \to \mu^+\mu^-$ and e^+e^- decay channels. Combining the $\mu^+\mu^-$ and e^+e^- final states and using the sequential SM (SSM) extension, the production of an SSM Z′ boson has been excluded at 95% confidence level (CL) for masses below 5.15 (5.10) TeV in searches reported by CMS [1] (ATLAS [5]). The SSM assumes that the Z′ boson has the same couplings to SM particles as those of the Z boson, in particular, couplings to SM fermions that are independent of their generation. There are several models that instead propose preferential couplings of the Z′ boson to third-generation fermions [6, 7]. In models with nonuniversal lepton couplings, assuming a Z′ boson with the same couplings to third generation fermions as the SM Z boson, bounds on $m_{Z'}$ are found for the $Z' \to \tau^+\tau^-$ decay mode [8, 9] excluding $m_{Z'}$ up to 2.42 TeV and the $Z' \to b\overline{b}$ decay mode [10, 11] excluding $m_{Z'}$ up to 2.7 TeV.

In recent years, interest in potential effects beyond the SM has emerged as a result of anomalies observed in the precision measurements of B meson decay rates, including $R(D^{(*)})$ [12–22], the ratio of branching fractions with leptons of different flavors. The $R(D^{(*)})$ ratio is sensitive to the violation of lepton flavor universality in $b \to cl\overline{\nu}_l$ transitions, where l denotes any lepton flavor. These anomalies have led to the proposal of a large number of theoretical models that predict the existence of heavy neutral and charged gauge bosons (Z′ and W′, respectively) with nonuniversal fermion couplings within a new $SU(2)$ group. These models further motivate the search for a Z′ boson that preferentially couples to third-generation fermions [23, 24]. For this search, we use a simplified phenomenological model, in which the Z′ boson mass and couplings are treated as free parameters [25]. In this paper, we consider a Z′ boson with the same fermion couplings as the Z boson to compare with previous searches, but also consider scenarios with varied Z′ boson couplings to the τ leptons.

This paper presents a search for a Z′ boson via the $\tau^+\tau^-$ decays, considering production via quark-antiquark annihilation, in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV at the LHC. The data were collected with the CMS experiment during 2016–2018, and correspond to an integrated luminosity of 138 fb^{-1}. Tabulated data are provided in the HEPData record [26] for this analysis.

The remaining sections of this paper present the analysis strategy, in Section 2, followed by a short detector description in Section 3. The event reconstruction is detailed in Section 4 and the generation of simulated samples in Section 5. We describe the event selection criteria and background estimation in Sections 6 and 7, respectively, for each of the τ pair decay channels. Taking into account systematic uncertainties as discussed in Section 8, we present the results in Section 9 and a summary in Section 10.

2 Analysis strategy

The τ decay channels can be broadly classified into hadronic (τ_{h}), ν_τ + hadrons, and leptonic (τ_ℓ), $\nu_\tau + \ell + \overline{\nu}_\ell$, with ℓ representing μ or e. The analysis presented here includes the three $\mathrm{Z}' \to \tau^\pm\tau^\mp$ decay channels with the largest τ decay branching fraction products: $\mathrm{Z}' \to \tau_\mu^\pm\tau_{\mathrm{h}}^\mp$, $\mathrm{Z}' \to \tau_{\mathrm{e}}^\pm\tau_{\mathrm{h}}^\mp$, and $\mathrm{Z}' \to \tau_{\mathrm{h}}^+\tau_{\mathrm{h}}^-$, referred to below as $\tau_\mu\tau_{\mathrm{h}}$, $\tau_{\mathrm{e}}\tau_{\mathrm{h}}$, and $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$, respectively.

In the production of Z′ bosons via s-channel annihilation of quark-antiquark pairs, the Z′ bosons have limited Lorentz boost in the plane transverse to the beam. For the TeV-scale $m_{\mathrm{Z}'}$ of interest, the τ decay daughters tend to be clustered within small back-to-back cones. With this picture in mind, we derive an estimate of the Z′ boson candidate mass $m_{\mathrm{rec}}(\mathrm{Z}')$, making use of the transverse momentum imbalance between the visible daughters of the two τ lepton decays:

$$m_{\mathrm{rec}}(\mathrm{Z}') = \sqrt{(E_1^{\tau\mathrm{vis}} + E_2^{\tau\mathrm{vis}} + |\mathbf{p}^{\mathrm{Z}'\mathrm{miss}}|)^2 - |\mathbf{p}_1^{\tau\mathrm{vis}} + \mathbf{p}_2^{\tau\mathrm{vis}} + \mathbf{p}^{\mathrm{Z}'\mathrm{miss}}|^2}. \quad (1)$$

Here $(E_i^{\tau\mathrm{vis}}, \mathbf{p}_i^{\tau\mathrm{vis}})$ is the four momentum of the reconstructed daughter(s) of the i^{th} τ candidate. The momentum of the invisible neutrinos is represented by $\mathbf{p}^{\mathrm{Z}'\mathrm{miss}} = (\vec{p}_{\mathrm{T}}^{\,\mathrm{Z}'\mathrm{miss}}, p_z^{\mathrm{Z}'\mathrm{miss}})$, with $\vec{p}_{\mathrm{T}}^{\,\mathrm{Z}'\mathrm{miss}} = -(\vec{p}_{1\mathrm{T}}^{\,\tau\mathrm{vis}} + \vec{p}_{2\mathrm{T}}^{\,\tau\mathrm{vis}})$ and $p_z^{\mathrm{Z}'\mathrm{miss}} = 0$. The momentum term $|\mathbf{p}_1^{\tau\mathrm{vis}} + \mathbf{p}_2^{\tau\mathrm{vis}} + \mathbf{p}^{\mathrm{Z}'\mathrm{miss}}|^2$ under the square root in Eq. 1 serves to subtract the longitudinal momentum components of the visible energy terms. We find that this method of accounting for the neutrinos provides better discrimination between the signal and the SM background processes than the event momentum imbalance $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$, the negative vectorial sum of all reconstructed objects. This is because $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ includes contributions from mismeasured jets in the underlying event and from additional pp interactions within the same or nearby bunch crossings (pileup).

We use $m_{\mathrm{rec}}(\mathrm{Z}')$ as the primary discriminating variable for extraction of the signal yield. Although the natural decay width of the Z′ boson is small compared with its mass (<3% for the model assumptions in this paper), the relative resolution on $m_{\mathrm{rec}}(\mathrm{Z}')$ is between 30 and 45% for the range of $m_{\mathrm{Z}'}$ considered. The analysis is thus dominated by experimental resolution effects arising from the undetected neutrinos. Data and simulation are used to obtain estimates of the yields of the SM background processes, and the signal yield is obtained from a maximum likelihood (ML) fit to the $m_{\mathrm{rec}}(\mathrm{Z}')$ distributions for each of the three $\mathrm{Z}' \to \tau^\pm\tau^\mp$ decay channels, as described in the following sections.

3 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are reconstructed in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [27, 28].

Events of interest are selected using a two-tiered trigger system. The first level, 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 fixed latency of about 4 μs [29]. The second level, known as the high-level trigger, 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 around 1 kHz before data storage [30].

4 Object reconstruction

The first stage of particle reconstruction employs the particle-flow (PF) algorithm [31], which aims to reconstruct and identify each individual visible particle in an event (photon, electron, muon, charged hadron, neutral hadron) with an optimized combination of all subdetector information. Further identification (ID) strategies for particular particle types are applied to achieve an appropriate balance between efficiency and the purity of the resulting candidate collections.

In the presence of pileup, the primary vertex, at which the pp collision of interest occurs, is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [32].

Jets are reconstructed offline from PF candidates using the anti-k_T clustering algorithm [33, 34] with a distance parameter of 0.4. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5 to 10% of the true momentum over the entire p_T spectrum and detector acceptance. Pileup interactions can contribute additional tracks and calorimetric energy depositions, increasing the apparent jet momentum. To mitigate this effect, tracks identified to be originating from pileup vertices are discarded, and an offset correction is applied to correct for remaining contributions [35]. Jet energy corrections are derived from simulation studies so that the average measured energy of jets matches that of particle level jets. In situ measurements of the momentum balance in dijet, photon + jet, Z + jet, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and appropriate corrections are made [36]. Additional selection criteria are applied to each jet to remove jets potentially dominated by instrumental effects or reconstruction failures [35].

The $\vec{p}_T^{\,miss}$ vector is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, modified to account for corrections to the energy scale of the reconstructed jets in the event [37]. Its magnitude is denoted p_T^{miss}.

Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. The single-muon trigger efficiency exceeds 90% over the full η range, and the efficiency to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution of 1% in the barrel and 3% in the endcaps for muons with p_T up to 100 GeV. The p_T resolution in the barrel is better than 7% for muons with p_T up to 1 TeV [38]. This analysis uses the tight working point [38] of the muon ID. To suppress muons from hadronization and other backgrounds, an additional requirement is imposed on the relative isolation, defined as the ratio of the energy from neutral and charged PF candidates in a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ around the muon trajectory to that of the muon. A correction for energy mismeasurement from pileup is applied, and we require this corrected relative isolation to be smaller than 0.15.

Electrons are reconstructed using energy deposits in the ECAL detector that have a matching track in (η, ϕ) space in the silicon tracking system, within $|\eta| < 2.4$. Electron candidates that fall in the transition region between the barrel and the endcap of the CMS detector, located at $1.44 < |\eta| < 1.57$, are not considered. The momentum resolution for electrons with $p_T \approx$

45 GeV from $Z \rightarrow ee$ decays ranges from 1.6–5.0%. It is better in the barrel region than in the endcaps, and depends on the bremsstrahlung energy emitted by the electron as it traverses the material in front of the ECAL [39, 40]. To identify electrons, we use the high-energy electron pairs (HEEP) ID for the selection of signal events; for veto and control region (CR) selections, we use instead the loose working point of the cut-based electron ID [40]. Isolation is defined as the amount of energy in a cone of $\Delta R < 0.3$ around the electron direction. It is an integral part of both electron ID criteria used, as defined in detail in [40], and both IDs utilize electron-energy-dependent isolation criteria with pileup energy corrections that differ between the barrel and endcap regions of the detector.

Hadronic τ lepton decays are reconstructed from jets using the hadrons-plus-strips algorithm [41], which combines 1 or 3 tracks with energy deposits in the calorimeters to form τ_h candidates. Neutral pions are reconstructed as strips with dynamic size in (η, ϕ) from reconstructed electrons and photons, where the strip size varies as a function of the p_T of the electron or photon candidate.

The DEEPTAU deep neural network algorithm [42] is used to distinguish genuine τ_h candidates from jets originating from the hadronization of quarks or gluons, and from electrons or muons. Information from all individually reconstructed particles near the τ_h momentum direction is combined with properties of the τ_h candidate and of the event. We make use of the tight (medium) working point for the discrimination of τ_h from muons (electrons), and of the tight, loose, and very loose working points for discrimination against jets, as described in Sections 6 and 7.

To identify jet candidates from b quark hadronization (hereafter denoted b jets) we use the DEEPCSV b tagging algorithm [43], which is based on a deep neural network. We employ the tight working point of the discriminator, for which the typical efficiency is 50%, while the mistag rate of jets originating from light-flavored quarks or gluons is 0.1% and from c jets is 2.4%.

5 Simulated samples

Monte Carlo simulation is used in the analysis to design the event selection and to model the signal and SM background processes. For estimates of the background yields we use a combination of simulation and data, as described in Section 7.

The background from SM events composed uniquely of jets produced via the strong interaction is referred to as quantum chromodynamics (QCD) multijet events. Events from Drell–Yan (DY), QCD multijet, single t quark, and W + jets processes are simulated with the MADGRAPH5_aMC@NLO 2.6.0 event generator [44] at leading order (LO) accuracy. The POWHEG 2.0 [45–47] event generator at next-to-LO (NLO) accuracy in QCD is used to simulate $t\bar{t}$ events, while diboson (VV) processes are produced at LO with PYTHIA 8.226 (8.230) for data taken in 2016 (2017 and 2018) [48].

Signal events are generated using MADGRAPH5_aMC@NLO at LO. A set of samples is produced for Z' boson masses ranging from 250 to 3000 GeV in steps of 250 GeV, as well as at 4000 and 5000 GeV. The primary set of benchmark signal samples for interpretation of the results have the Z' boson couplings set to SM Z values. Additionally, scenarios with varied modifiers g_τ of the couplings to τ leptons are considered. The theoretical decay width of the Z' boson in the production model increases with g_τ but remains smaller than the experimental resolution (<30%) for the range of g_τ values considered in this study. Therefore, varying g_τ values only affects the Z' branching fraction in this analysis and thus the results of this analysis can be reinterpreted by scaling the theoretical cross section by the appropriate branching fraction.

The MADGRAPH5_aMC@NLO and POWHEG generators used to simulate signal and background processes are interfaced with PYTHIA 8.226 (8.230) using the CUETP8M1 (CP5) tunes [49, 50] for parton showering and fragmentation in the 2016 (2017–2018) simulated samples. The NNPDF3.0 (3.1) NNLO [51] parton distribution functions (PDFs) are used in the event generation for 2016 (2017–2018) samples. The simulated background yields are normalized to the integrated luminosity using next-to-NLO or NLO cross sections [44, 52–62], while signal production cross sections are calculated at NLO accuracy.

The detector response is modeled with GEANT4 [63]. Pileup is incorporated by simulating additional interactions with timing and population distributions matching those measured in data.

6 Event selection criteria

The signal region (SR) selection criteria for each $Z' \to \tau^+\tau^-$ decay channel are chosen to maximize the expected signal significance by balancing signal efficiency against the suppression of background. The main SM background processes are DY, W + jets, $t\bar{t}$, QCD multijet, and VV (WW, ZZ, and WZ) production. The DY process constitutes an irreducible background since $\tau^+\tau^-$ pairs arise from the intermediate Z and photon states. However, since the analysis focuses on massive Z' bosons, the visible daughters from the two τ lepton decays typically have higher momentum and larger angular separation than those from DY events. We exploit these characteristics to separate heavy Z' boson signals from background. Events from W + jets and $t\bar{t}$ are a background for the $\tau_\ell\tau_h$ final states when the W boson, produced directly or from a top quark decay, decays via $W \to \ell\nu_\ell$, and a jet is misidentified as a τ_h candidate. Events from VV or $t\bar{t}$ production with leptonic decays of both vector bosons produce genuine lepton pairs, leading to the same $\tau^+\tau^-$ final states as signal events. Multijet events become a background source through the misidentification of jets as τ_h or ℓ candidates.

Events are required to have one τ_h candidate accompanied by a μ, e, or second τ_h candidate of opposite-sign (OS) charge, all within $|\eta| < 2.1$. To avoid possible overlaps among the three channels, we reject events containing additional lepton candidates of any flavor beyond the selected OS lepton candidate pair. Specifically, the additional lepton can be a μ or e candidate with $p_T > 10\,\text{GeV}$ and $|\eta| < 2.1$, or a τ candidate meeting the τ_h requirements of the particular channel. Since the analysis explores the production of Z' bosons through quark-antiquark annihilation, events from vector boson fusion are suppressed by vetoing events with a pair of jets $j^{1,2}$ having $p_T > 30\,\text{GeV}$, $|\eta| < 4.7$, a pseudorapidity separation $|\Delta\eta(j^1, j^2)| > 4.2$, and an invariant mass above 500 GeV.

For the ID of τ_h candidates in the SRs for all decay channels we impose the tight working points of the discriminators against jets and muons, and the medium one against electrons, as defined in Ref. [42]. The probability of misidentifying a jet as a τ_h candidate depends on the p_T and flavor of the jet; for the kinematic conditions of this analysis it has been estimated in a W + jets sample to be approximately 0.6%, with a genuine τ_h ID efficiency of 60%. The probability for muons (electrons) to be misidentified as τ_h candidates is 0.07% (0.2%) for a genuine τ_h ID efficiency of >99% (90%).

6.1 The $\tau_\mu \tau_\mathrm{h}$ SR

The $\tau_\mu \tau_\mathrm{h}$ events are required to satisfy the single-muon trigger, whose efficiency exceeds 90% over the full η range after the selection of muon candidates with $p_\mathrm{T} > 35\,\mathrm{GeV}$. Muons are also required to be well isolated, and pass the tight ID criteria defined in Ref. [38]. The τ_h candidate is required to satisfy $p_\mathrm{T} > 20\,\mathrm{GeV}$. The two candidates are required to be well separated in (η, ϕ) space by the criterion $\Delta R \equiv \sqrt{(\Delta\phi(\tau_\mu, \tau_\mathrm{h}))^2 + (\Delta\eta(\tau_\mu, \tau_\mathrm{h}))^2} > 0.3$. We reject events containing b jet candidates with $p_\mathrm{T} > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$. Events from DY, W + jets, and QCD multijet production are significantly suppressed by requiring the τ_μ and τ_h candidates to have a large azimuthal separation given by $\cos\Delta\phi(\tau_\mu, \tau_\mathrm{h}) < -0.98$. In addition, we require that $\vec{p}_\mathrm{T}^\mathrm{miss}$ lie in the direction opposite that of the τ_h or of the τ_μ candidate with the highest p_T (leading lepton, ℓ^1), by requiring $\cos\Delta\phi(p_\mathrm{T}^\mathrm{miss}, \ell^1) < -0.95$. This requirement further reduces the contribution of W + jets and QCD multijet events. The transverse mass of the leading lepton and $\vec{p}_\mathrm{T}^\mathrm{miss}$, $m_\mathrm{T}(p_\mathrm{T}^\mathrm{miss}, \ell^1) = \sqrt{p_\mathrm{T}^\mathrm{miss} p_\mathrm{T}(\ell^1)(1 - \cos(\Delta\phi(p_\mathrm{T}^\mathrm{miss}, \ell^1)))}$, is required to be greater than 150 GeV for further suppression of W + jets events.

6.2 The $\tau_\mathrm{e} \tau_\mathrm{h}$ SR

Similar selection criteria are applied to the $\tau_\mathrm{e} \tau_\mathrm{h}$ channel, with the following differences. We require these events to satisfy a single-electron trigger that has an efficiency above 90% for electrons after the requirements $p_\mathrm{T} > 35\ (55)\,\mathrm{GeV}$ for data collected in 2016 (2017–2018).

6.3 The $\tau_\mathrm{h} \tau_\mathrm{h}$ SR

For the $\tau_\mathrm{h} \tau_\mathrm{h}$ channel we select events that satisfy a dedicated trigger [29] with at least two τ_h candidates. We require each τ_h candidate to have $p_\mathrm{T} > 70\,\mathrm{GeV}$, ensuring a trigger efficiency of at least 90%. The two τ_h candidates must be separated by $\Delta R > 0.3$. Events with any b jet candidate having $p_\mathrm{T} > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$ are removed, to suppress top quark backgrounds. To reduce the contribution of DY events, the reconstructed mass of the τ_h pair is required to exceed 100 GeV. To discriminate against W + jets and QCD multijet events, we require the two τ_h candidates to have a large azimuthal separation, $\cos\Delta\phi(\tau_\mathrm{h}^1, \tau_\mathrm{h}^2) < -0.95$, while the $\vec{p}_\mathrm{T}^\mathrm{miss}$ and the leading-p_T τ_h candidate ${\tau_\mathrm{h}}^1$ are required to satisfy $|\cos\Delta\phi(p_\mathrm{T}^\mathrm{miss}, {\tau_\mathrm{h}}^1)| > 0.9$. Further suppression of the contribution of QCD multijet events is achieved with a requirement $p_\mathrm{T}^\mathrm{miss} > 30\,\mathrm{GeV}$.

7 Background estimation

The background yields are estimated in discrete intervals (bins) in the variable $m_\mathrm{rec}(\mathrm{Z}')$, by methods that depend on the SM process and the channel. In most cases, these estimates are based on samples of simulated events. Differences between data and simulation with respect to the efficiency of triggers, particle ID or isolation, and energy scale and resolution of electrons, muons, jets, and $p_\mathrm{T}^\mathrm{miss}$ are taken into account with dedicated correction factors whose uncertainties are propagated throughout. These correction factors are described in the references cited in Section 4. Residual mismodeling can remain due to systematic effects of the theoretical predictions, or to the phase space requirements specific to this analysis or to a specific channel. To ensure that the effect of any such mismodeling and its uncertainty in the background yield is accounted for, we evaluate a data-to-simulation scale factor (SF) in a CR. Validation tests are performed using additional simulation and data control samples to ensure the correct determination of the SFs and their applicability to the SR background prediction. The systematic uncertainties in the SFs account for correlations between the CRs.

The SFs are found to be approximately independent of $m_{rec}(Z')$, and are thus applied to the $m_{rec}(Z')$ distributions as bin-independent normalization factors. Uncertainties from the residual shape dependence are evaluated as described in Section 8. The SFs are derived for each data-taking year separately, along with their uncertainties and year-to-year correlations. The values of the SFs and their uncertainties are given in the following subsections. With a few exceptions, these values are consistent with unity. In the case of the QCD multijet background, the estimate is derived from the yield measured in dedicated orthogonal data control samples using the ABCD method described in Section 7.1. For SM processes that contribute less than 5% to the background yield, the simulation is taken directly.

Each CR is constructed to be enriched in a given SM process and orthogonal to the corresponding SR, but with characteristics similar to those of the SR. We correct for contamination from other SM processes by subtracting their SF-corrected simulated yields. The resulting dependence of the estimate of one background process on the SF for another is treated through the uncertainty correlation terms in the ML fit.

7.1 The $\tau_\ell\tau_h$ CRs

The main sources of background events in the $\tau_\ell\tau_h$ channels are DY, W + jets, and $t\bar{t}$ production.

To derive the SFs for the DY background in the $\tau_\ell\tau_h$ channels we define CRs by selecting events as for the SRs except for an inverted m_T criterion, $m_T < 150$ GeV, and a requirement that the reconstructed mass of the $\tau_\ell\tau_h$ pair lie within the Z boson mass window, $70 < m_{rec}(\tau_\ell\tau_h) < 110$ GeV. Since the higher p_T threshold for electrons of 55 GeV in 2017–2018 would deplete the low end of this mass range for a $\tau_e\tau_h$ CR, for those data sets we substitute the SFs measured in the corresponding $\tau_\mu\tau_h$ channels. The values of the DY SFs for the $\tau_\ell\tau_h$ channels are 1.11 ± 0.10, 0.96 ± 0.09, and 0.90 ± 0.08 in 2016, 2017, and 2018, respectively.

We measure the SF for the W + jets background in a CR defined to be orthogonal to the SR by inverting the τ_h selection, i.e., by requiring that the τ_h candidates fail the tight discrimination against jets while passing the very loose selection. We also modify the $m_T > 150$ GeV SR requirement so as to include W boson production; we select events with $m_T < 190$ GeV, where the extended upper limit serves to probe the W + jets background in the high mass tail of the $m_{rec}(Z')$ distribution. The contribution of QCD multijet events in this CR is nonnegligible, amounting to 30–40% depending on the channel and data-taking year; it is estimated from data following the same methodology as that described below in this section for estimating the QCD multijet background in the SR. In the $\tau_\mu\tau_h$ channel, the SFs are 0.98 ± 0.03, 0.98 ± 0.03, and 0.92 ± 0.03 in 2016, 2017, and 2018, respectively. For the $\tau_e\tau_h$ channel, the SFs are 1.02 ± 0.07, 0.94 ± 0.08, and 0.92 ± 0.09 in 2016, 2017, and 2018, respectively.

For $t\bar{t}$ events, we define the CR by imposing the SR selection criteria but changing the required number of b jet candidates from zero to exactly one. The requirement of exactly one b jet candidate ensures that the CR is kinematically similar to the SR. For 2016, 2017 and 2018, the SFs in the $\tau_\mu\tau_h$ ($\tau_e\tau_h$) channel are 1.02 ± 0.07, 0.80 ± 0.04, and 0.82 ± 0.04 (0.90 ± 0.11, 0.85 ± 0.05, and 0.85 ± 0.05), respectively.

In all CRs we find agreement between data and simulation in the $m_{rec}(Z')$ spectrum, after the corresponding SFs are applied to the simulation.

For the QCD multijet background we apply an ABCD method, in which the space of measured observables is projected onto two dimensions and divided into orthogonal regions. The necessary lack of correlation between the two inversion arguments has been validated in a separate

ABCD set with $p_{\mathrm{T}}^{\mathrm{miss}} < 30\,\mathrm{GeV}$ in the hadronic di-tau channel, where QCD contributes most to the total background. The estimate of the background yield N_{A} in the SR is determined from the yields in CRs B, C, and D as $N_{\mathrm{A}} = (N_{\mathrm{C}}/N_{\mathrm{D}})N_{\mathrm{B}}$. Here the first observable is the charge-sign pairing of the τ candidates: the OS requirement of the SR is reversed to same-sign (SS) to define CR B. The second observable is the appropriate measure of τ purity, namely lepton ID for τ_{ℓ}, isolation for τ_{h}: both tight, as in the SR, for region B, at least one loose and not tight for regions C (OS) and D (SS). A systematic uncertainty in the assumption that $N_{\mathrm{A}}/N_{\mathrm{B}} = N_{\mathrm{C}}/N_{\mathrm{D}}$ is evaluated with an additional CR, as discussed in Section 8. The calculation is performed for each bin of the $m_{\mathrm{rec}}(\mathrm{Z}')$ distribution.

7.2 The $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ CRs

The main sources of background events in the $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ channel are DY and QCD multijet events.

For the DY component, the SF is measured in a CR defined by the SR criteria except that the τ_{h} candidate pair's invariant mass $m(\tau_{\mathrm{h}}, \tau_{\mathrm{h}})$ is required to satisfy $m(\tau_{\mathrm{h}}, \tau_{\mathrm{h}}) < 100\,\mathrm{GeV}$. The DY SFs measured for the $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ channel are 1.11 ± 0.10, 0.96 ± 0.09, and 0.90 ± 0.08 in 2016, 2017, and 2018, respectively.

The QCD multijet background is estimated with an approach similar to that described in Section 7.1. Again a CR B is selected by the SR criteria except requiring an SS τ candidate pair. The common requirements for the events in the C and D CRs are $p_{\mathrm{T}}^{\mathrm{miss}} < 30\,\mathrm{GeV}$, and that the τ candidates fail the tight, while passing the very loose, discrimination against jets. Events entering CR C (D) pass the OS (SS) charge requirements.

7.3 The CR mass distributions

Figure 1 shows the $m_{\mathrm{rec}}(\mathrm{Z}')$ distributions for the data and simulation in the CRs that are used to compute the SFs. Here the yields are summed over the data-taking years and are measured prior (pre-fit) to the ML fit that is used to extract the signal yields.

8 Systematic uncertainties

We account for systematic uncertainties associated with the various sources as detailed in the following paragraphs.

The integrated luminosities for the 2016, 2017, and 2018 data-taking years have individual uncertainties of 1.2–2.5% [64–66], while the overall uncertainty for the 2016–2018 period is 1.6%. This uncertainty is applied to all background and signal processes.

Uncertainties in the pileup modeling corrections are evaluated by varying the total inelastic pp cross section used in the correction procedure by $\pm 5\%$ [67, 68]. The effect of the resulting change in the distribution of the number of primary vertices is less than 0.01%, and is therefore treated as negligible.

The efficiencies for the electron and muon reconstruction, ID, and isolation are measured with a "tag-and-probe method" [38, 40, 69] with a resulting uncertainty of $\leq 2\%$, depending on p_{T} and η. The total efficiency for the τ_{h} ID and isolation requirements is measured from a fit to the $\mu\tau_{\mathrm{h}}$ invariant mass distribution from $\mathrm{Z} \to \tau\tau$ events, not taking into account neutrino hypotheses or $p_{\mathrm{T}}^{\mathrm{miss}}$. This is done in a sample selected with one isolated μ trigger candidate with $p_{\mathrm{T}} > 24\,\mathrm{GeV}$, and leads to a relative uncertainty of less than 9% per genuine τ_{h} candidate [41], dependent on p_{T} and η. These uncertainties have contributions that are either statistical and thereby uncorrelated, or systematic and therefore correlated across the data-taking years. In

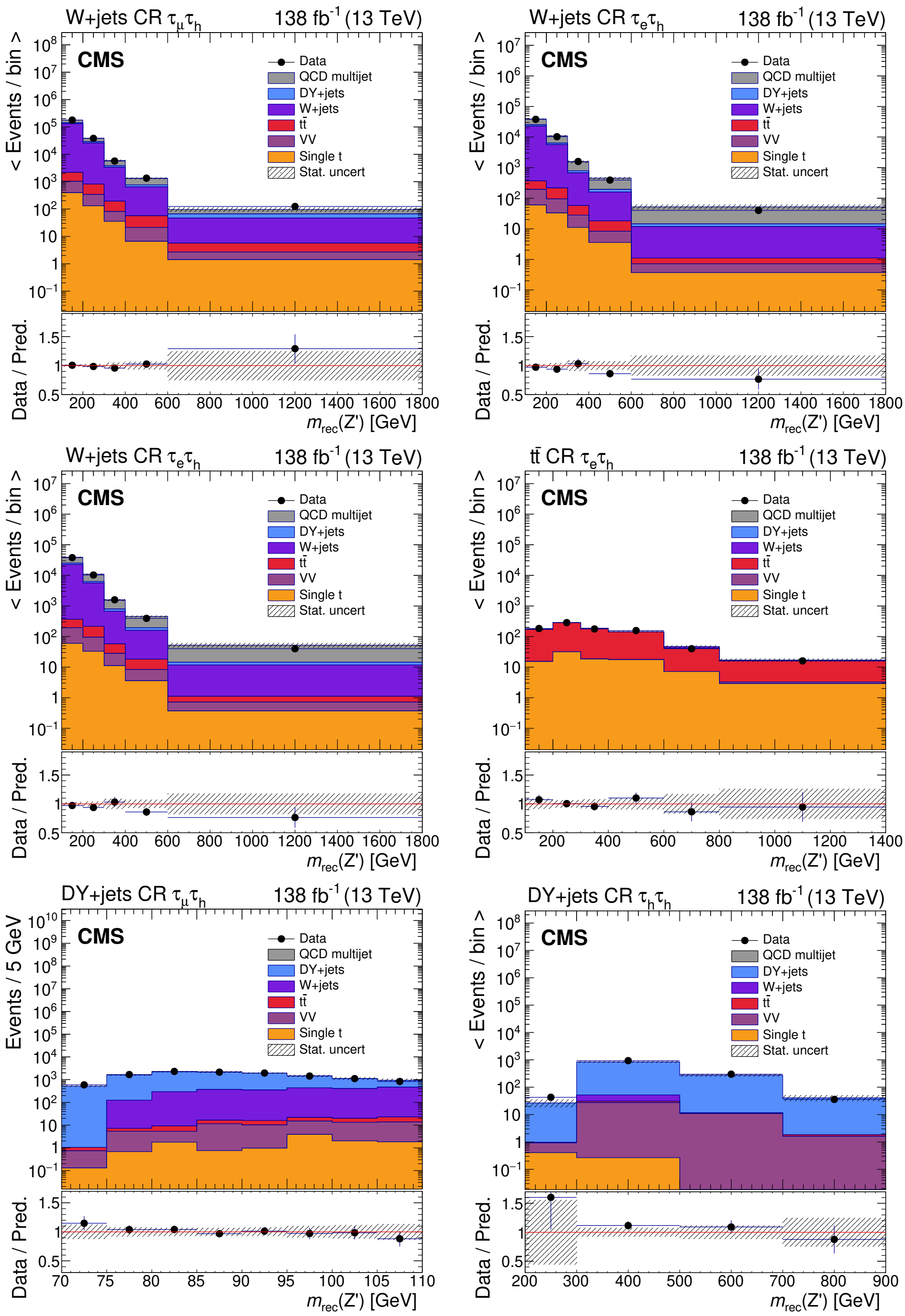

Figure 1: Pre-fit reconstructed mass distributions for the (upper row) W + jets, (middle row) $t\bar{t}$, and (lower row) DY CRs, for the (left column) $\tau_\mu\tau_h$, (right column, upper and middle rows) $\tau_e\tau_h$, and (lower right) $\tau_h\tau_h$ channel. The targeted background in each CR, denoted by its CR name, has been corrected with the derived SF from that CR. The background contributions appear as stacked solid histograms, while the data are shown as black solid markers with error bars. Overflow counts are included in the last bin. The gray shadow band represents the statistical uncertainty in the background prediction based on the number of simulated events and SF uncertainties. The lower panel of each plot shows the ratio of data to predicted background yields.

the cases where background estimates rely on the modeling of the misidentification of jets as τ_h candidates, additional systematic uncertainties in the corresponding background yields are assigned that range from 20 to 30%.

For the lepton momentum scale, the reconstructed momentum is shifted by 5% and the $\vec{p}_T^{miss}$ vector recalculated. This results in a change in the expected signal yield of 1–6%, depending on $m_{Z'}$, and negligible change for the backgrounds. The corresponding resolution uncertainty in the simulation is taken as 0.03 times the difference between the reconstructed and true values of the lepton's momentum [38]. It is found to have negligible impact on either signal or background yields.

Similarly, we include the uncertainties in the energy scale and resolution of jets and the propagation thereof to p_T^{miss} [36]. The impact on the SR selection is indirect, affecting only the vetos on b-tagged jets and VBF dijet candidates. Accordingly, the signal event yield is not affected by either uncertainty, while the background event yields vary, depending on the process, by less than 2%.

We propagate the uncertainty in the b jet mistagging SF [43] to its effect on the b jet requirements in the SR selection. The resulting uncertainty in the signal yield is found to be $\sim$1%. The effect of the b tagging efficiency uncertainty on the mass distribution in the $t\bar{t}$ CRs for the $\tau_\ell\tau_h$ channels is measured by varying the b tagging SF up and down by its uncertainty; the resulting uncertainty in the $t\bar{t}$ SF is about 2%.

The uncertainties in the cross sections used to predict the rates of various processes, which arise primarily from the factorization and renormalization scale choices and the PDFs, are propagated to the yield estimates. The cross section uncertainties are each separated into their scale (renormalization and factorization scales) and PDF components. They are correlated where appropriate among processes. To derive systematic uncertainties in the predicted signal yields arising from the choice of PDFs used in the simulation, we vary the PDFs following the PDF4LHC prescription [70]. We find that these variations do not affect the shapes of kinematic distributions, but the resulting systematic uncertainty in the overall signal acceptance prediction is 2–6%, depending on the assumed value of $m_{Z'}$.

Uncertainties in the renormalization and factorization scales are evaluated as the differences in predicted signal yields as these scales are varied independently from their default values by factors of 2.0 and 0.5 [71]. The resulting uncertainties in the yields are <2%, independent of $m_{Z'}$.

The statistical uncertainty associated with the SFs measured in the CRs is propagated to the total uncertainty in the expected yields in the SR. The SFs in the $t\bar{t}$ CRs, where some dependence on $m_{rec}(Z')$ is observed, are fit with a first-order polynomial as a function of $m_{rec}(Z')$. The deviation of the resulting function from unity is taken as the systematic uncertainty in the shape. The effect spans the range 1–22%, depending on the $m_{rec}(Z')$ bin and data-taking year.

For the QCD transfer factors N_C/N_D, the statistical uncertainties are in the ranges 19–23% for $\tau_\mu\tau_h$, 23–26% for $\tau_e\tau_h$, and 1.7–2.1% for $\tau_h\tau_h$. For each of the $\tau_\mu\tau_h$ and $\tau_e\tau_h$ channels, the QCD contribution to the SR is small (6–9%), while it is large for the $\tau_h\tau_h$ channel (27–35%), albeit mostly at low $m_{rec}(Z')$ and therefore of low relevance to high-$m_{Z'}$ signal scenarios. Closure tests in a low-p_T^{miss} sideband version of the ABCD method for the QCD estimation in the $\tau_h\tau_h$ channel show agreement within statistical uncertainties, and so no additional closure systematic uncertainty is applied. Instead, for all three channels, the transfer factors are fit with a first-order polynomial as a function of $m_{rec}(Z')$, and the deviation of this function from unity provides the $m_{rec}(Z')$ shape uncertainty. The resulting systematic uncertainties for the three channels are 2.0–150% ($\tau_\mu\tau_h$), 2.0–50% ($\tau_e\tau_h$), and 0.2–24% ($\tau_h\tau_h$), depending on the data-taking year and mass value.

9 Results

The signal strength is extracted from an ML fit of the data yields in the SRs for all bins of the $m_{rec}(Z')$ distribution, for all channels, and all data-taking years. The fit function is a sum of the corresponding predictions of the yields for the signal and for each of the SM background processes, with the signal strength as a free scale parameter modifying the signal prediction. Statistical uncertainties from the CRs and simulated samples, as well as all systematic uncertainties, are introduced as nuisance parameters, including their correlations. The nuisance parameters are constrained by log-normal penalty factors in the likelihood, which are uncorrelated across bins. Any cross-contamination among the CRs is accounted for by the correlation terms between the CRs. The contamination of CRs by the signal is found to be small (order of percent or less), and is neglected in the fit model. The ML fit is implemented with the CMS statistical analysis tool COMBINE [72].

Table 1 shows for each channel the estimated pre-fit event yield for each SM background contribution, together with the total background and the observed yields. The $m_{rec}(Z')$ distributions for the data and the SM background estimates as determined by the background-only fits (post-fit) are displayed for the three channels in Fig. 2. The lower panels compare the data with the pre-fit and post-fit estimates. The observed yields are consistent with the SM prediction.

Table 1: Pre-fit estimated background and observed event yields for the three channels in the SR. For each SM process the yield in events is shown, along with the percentile contribution to the total. The background SFs derived from the dedicated CRs are used to determine the listed background yields. The uncertainty associated with the event yields is statistical. The uncertainty in the background contributions adjusted by the SFs includes the uncertainty in the corresponding SF.

	$\tau_\mu\tau_h$		$\tau_e\tau_h$		$\tau_h\tau_h$	
Process	Events	%	Events	%	Events	%
W + jets	851 ± 86	24	717 ± 89	30	158 ± 16	10
DY	1315 ± 70	37	661 ± 34	28	920 ± 43	55
$t\bar{t}$	637 ± 21	18	468.1 ± 8.1	20	32.8 ± 1.6	2
Single t	157.4 ± 6.0	5	116.1 ± 5.4	5	5.5 ± 1.2	<1
VV	302.4 ± 7.7	9	247.5 ± 6.0	11	26.8 ± 1.8	2
QCD multijet	251 ± 44	7	135.0 ± 8.0	6	514 ± 27	31
Total background	3514 ± 122	100	2345 ± 96	100	1658 ± 53	100
Data	3737		2269		1549	

Using the CL_s criterion [73, 74], we compute an asymptotic approximation of the upper limit at 95% CL [75] on the product of the cross section and branching fraction $\sigma\mathcal{B}(Z' \to \tau^+\tau^-)$, as a function of $m_{Z'}$. Figure 3 shows the limits for each channel and Figure 4 the combination of the three channels. Due to the high branching fraction to hadronic τ lepton decays, the $\tau_h\tau_h$ channel contributes the most to these limits. There is no significant difference in impact between the mixed τ pair decay channels. The dashed lines represent the theoretical prediction for the branching fraction values of 1, 3, and 10%, where 3% is the approximate value of $\mathcal{B}(Z' \to \tau^+\tau^-)$ in the sequential standard model (SSM), considering $t\bar{t}$ decays to be kinematically allowed. The corresponding lower bounds on $m_{Z'}$ are 3.0, 3.5, and 4.1 TeV, respectively.

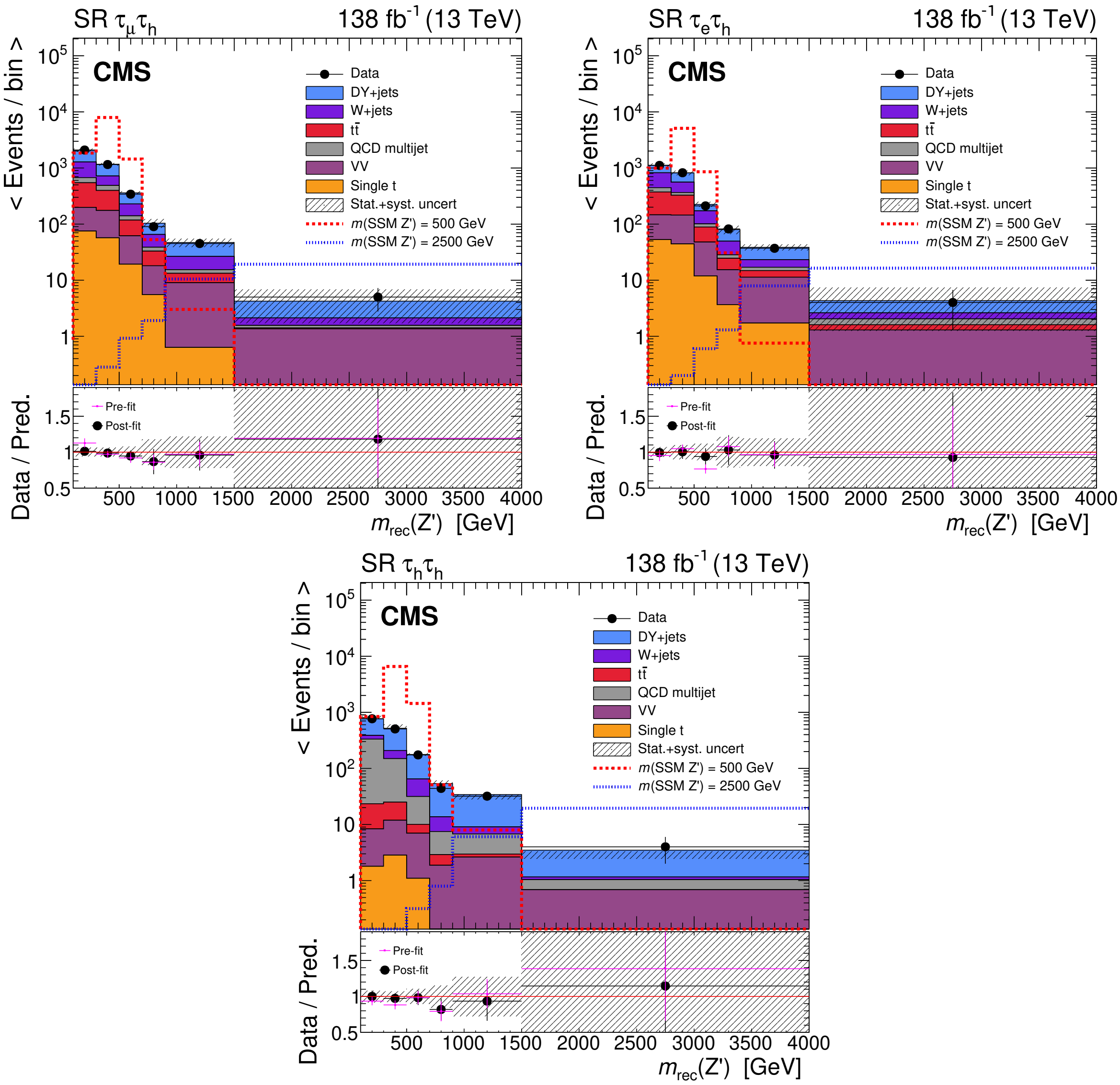

Figure 2: Post-fit reconstructed mass distributions for the (upper left) $\tau_\mu\tau_h$, (upper right) $\tau_e\tau_h$, and (lower) $\tau_h\tau_h$ channel. The background contributions appear as stacked solid histograms, while the observed data are shown as black solid markers with error bars. Overflow counts are included in the last bin. The gray shadow band represents the statistical plus systematic uncertainty in the post-fit background prediction. The ratio to the pre-fit background prediction is indicated in magenta markers in the ratio. The signal expectation is shown in lines for $m_{Z'}$ of 500 GeV (red dashed) and 2500 GeV (blue dotted), normalized to 1850 and 0.131 pb, respectively.

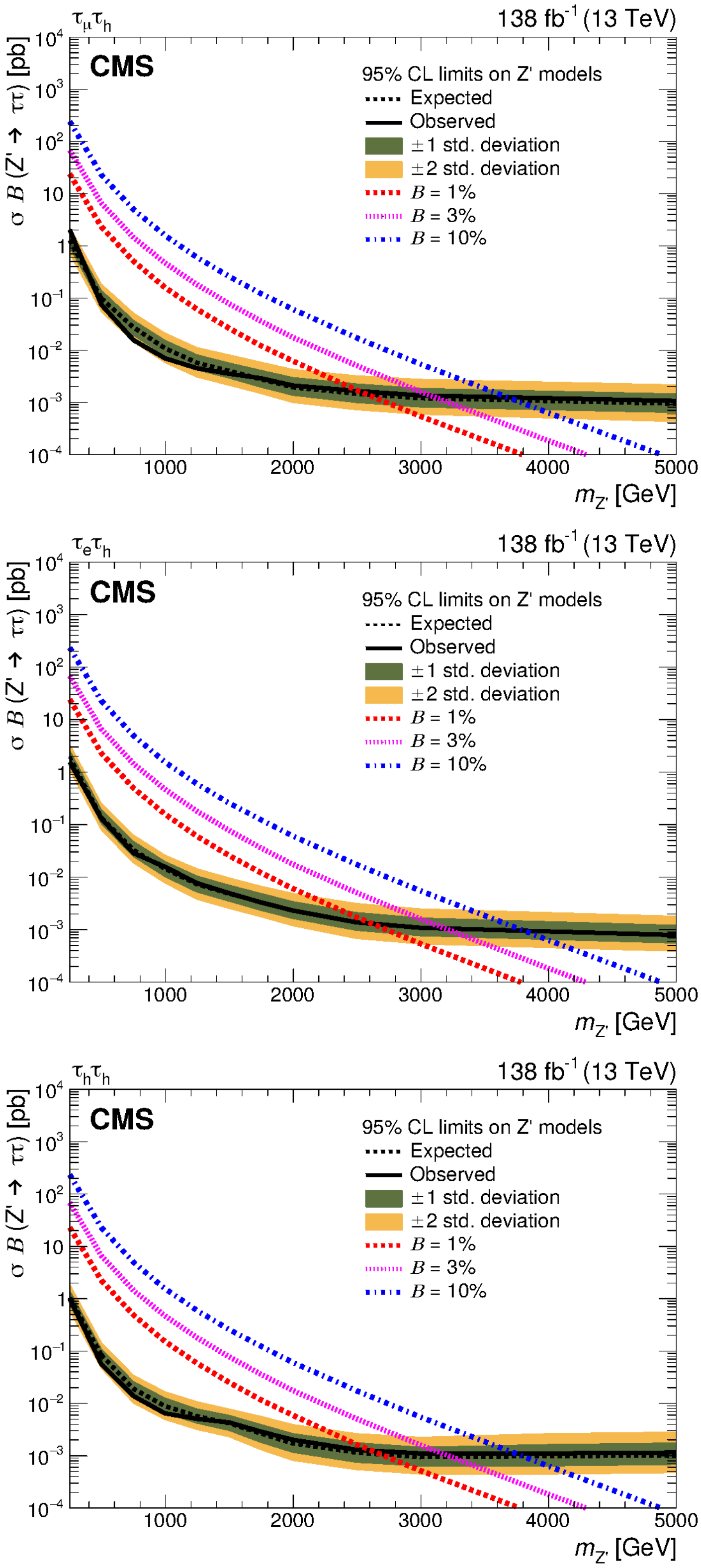

Figure 3: Upper limits at 95% CL on $\sigma\mathcal{B}(Z' \to \tau^+\tau^-)$ for the (upper) $\tau_\mu\tau_h$, (middle) $\tau_e\tau_h$, and (lower) $\tau_h\tau_h$ channel. In each plot, the solid black line represents the observed limit, and the black dashed line with green and yellow bands depicts the expected limit with its one- and two-standard deviation uncertainties, respectively. The red dashed, magenta dotted, and blue dash-dotted lines represent the theoretical predictions for $\mathcal{B}(Z' \to \tau^+\tau^-) = 1$, 3, and 10%, respectively; 3% is the value of $\mathcal{B}(Z' \to \tau^+\tau^-)$ in the SSM. These assume that the $\mathcal{B}(Z' \to \tau^+\tau^-)$ values are fixed for all $m_{Z'}$.

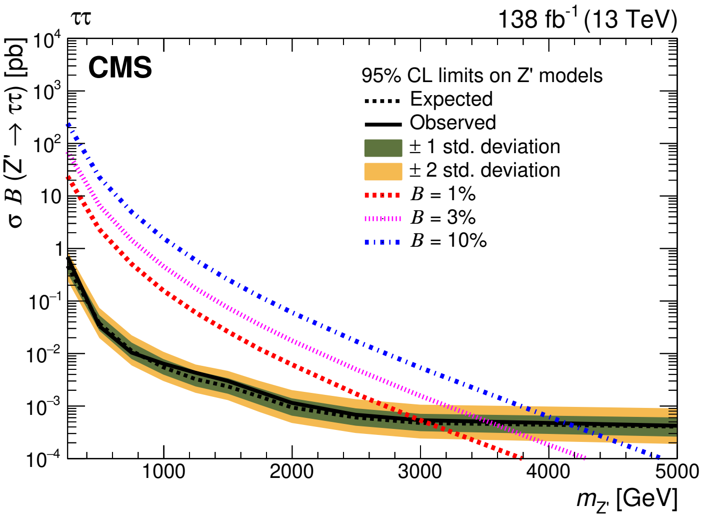

Figure 4: Upper limits at 95% CL on $\sigma\mathcal{B}(\mathrm{Z}' \to \tau^+\tau^-)$ for the combination of all channels. The solid black line represents the observed limit, and the black dashed line with green and yellow bands depicts the expected limit with its one- and two-standard deviation uncertainties, respectively. The red dashed, magenta dotted, and blue dash-dotted lines represent the theoretical predictions for $\mathcal{B}(\mathrm{Z}' \to \tau^+\tau^-) = 1$, 3, and 10%, respectively; 3% is the value of $\mathcal{B}(\mathrm{Z}' \to \tau^+\tau^-)$ in the SSM. These assume that the $\mathcal{B}(\mathrm{Z}' \to \tau^+\tau^-)$ values are fixed for all $m_{\mathrm{Z}'}$.

10 Summary

A search has been performed in proton-proton collisions at $\sqrt{s} = 13$ TeV for the production via quark-antiquark annihilation of a heavy neutral gauge boson Z' decaying to $\tau^+\tau^-$. The data were recorded at the LHC during 2016–2018, and correspond to an integrated luminosity of 138 fb^{-1}. As the tau lepton can decay hadronically (τ_h) or leptonically (τ_ℓ), with ℓ representing a muon or electron, the analysis includes the three decay channels with the highest τ lepton branching fraction products: $Z' \to \tau_\mu^\pm \tau_h^\mp$, $Z' \to \tau_e^\pm \tau_h^\mp$, and $Z' \to \tau_h^+ \tau_h^-$. An estimator $m_{rec}(Z')$ is constructed to approximate the Z' boson mass $m_{Z'}$ in the presence of undetected neutrino daughters from the τ lepton decays.

The main background processes are estimated using Monte Carlo simulation adjusted by scale factors derived from data. The observed yields are found to be consistent with the background prediction. A shape-based analysis is performed using the $m_{rec}(Z')$ distribution as the fit discriminant to determine the likelihood for the observed data in the presence of a signal and the predicted background contributions. The upper limit on the product of the Z' boson production cross section and decay branching fraction is set at 95% confidence level as a function of $m_{Z'}$.

In the scenario considered in this analysis, the data excludes a Z' boson with $m_{Z'}$ less than 3.0, 3.5, or 4.1 TeV for a branching fraction of 1, 3, or 10%, respectively. These exclusion limits are the most stringent to date for a Z' boson decaying to $\tau^+\tau^-$.

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