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Search for high-mass resonances decaying into τ -lepton pairs in pp collisions at √s = 7 TeV

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ABSTRACT

A search for high-mass resonances decaying into $\tau^+\tau^-$ is performed using a data sample of pp collisions at $\sqrt{s} = 7$ TeV. The data were collected with the CMS detector at the LHC and correspond to an integrated luminosity of 4.9 fb^{-1}. The number of observed events is in agreement with the standard model prediction. An upper limit on the product of the resonance cross section and branching fraction into τ-lepton pairs is calculated as a function of the resonance mass. Using the sequential standard model resonance Z'_{SSM} and the superstring-inspired E_6 model with resonance Z'_ψ as benchmarks, resonances with standard model couplings with masses below 1.4 and 1.1 TeV, respectively, are excluded at 95% confidence level.

1. Introduction

The standard model (SM) of elementary particles [1–3] provides a successful framework that describes a vast range of particle processes involving weak, electromagnetic, and strong interactions. It is widely believed, however, that the SM is incomplete since, e.g., it fails to incorporate the gravitational force, has no dark matter candidate, and has too many parameters whose values cannot be deduced from the theory. Many models of physics beyond the SM have been proposed to address these problems. A simple way of extending the SM gauge structure is to include an additional $U(1)$ group, which requires an associated neutral gauge boson, usually labeled as Z′ [4–7]. Although most studies have assumed generation-independent gauge couplings for Z′, models in which the Z′ couples preferentially to third generation fermions have also been proposed [7–10]. The sensitivity of the traditional searches for Z′ production using e^+e^- and $\mu^+\mu^-$ final states may be substantially reduced in such non-universal scenarios, motivating the exploration of other allowed final states. The sequential SM (SSM) includes a neutral gauge boson, Z'_{SSM}, with the same couplings to quarks and leptons as the SM Z boson. Although not gauge invariant, this model has been traditionally considered by experiments studying high-mass resonances. Other models, such as the superstring-inspired E_6 model, have more complex group structures, $E_6 \to SO(10) \times U(1)_\psi$, with a corresponding neutral gauge boson denoted as Z'_ψ [11]. In this Letter we present a search for heavy resonances that decay into pairs of τ leptons using the Z'_{SSM} and Z'_ψ models as benchmarks. A previous search reported by the CDF Collaboration has ruled out a Z'_{SSM} decaying into $\tau^+\tau^-$ with SM couplings with mass below 399 GeV [12].

About one-third of the time τ leptons decay into lighter charged leptons plus neutrinos, whereas the other two-thirds of the time τ leptons decay into a hadronic system with one, three, or five charged mesons, which can be accompanied by neutral pions in addition to the τ neutrino. We refer to the leptonic and hadronic decay channels as τ_ℓ ($\ell = e, \mu$) and τ_h, respectively. Four $\tau^+\tau^-$ final states, $\tau_e\tau_\mu$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, and $\tau_h\tau_h$, are studied using a sample of proton–proton collisions at $\sqrt{s} = 7$ TeV recorded by the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC). The data sample corresponds to an integrated luminosity of 4.94 ± 0.11 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 silicon pixel and strip tracker, the lead-tungstate ($PbWO_4$) crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). Muons are measured with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

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CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the counterclockwise-beam direction. The polar angle, θ, is measured from the positive z axis and the azimuthal angle, ϕ, is measured in the x–y plane.

The inner tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$; muons are measured within $|\eta| < 2.4$.

A more detailed description of the CMS detector can be found elsewhere [13].

3. Lepton reconstruction and identification

Electrons are reconstructed by combining clusters in the ECAL with tracks in the inner tracker fitted with a Gaussian sum filter algorithm [14]. Electron candidates are required to have good energy–momentum and spatial match between the ECAL cluster and the inner track. In addition, the ratio of the energies measured in HCAL and ECAL must be consistent with an electron signature.

Muons are reconstructed by matching hits found in the muon detectors to tracks in the inner tracker [15]. Quality requirements, based on the minimum number of hits in the silicon, pixel, and muon detectors, are applied to suppress backgrounds from punch-through and decay-in-flight pions. A requirement on the maximum transverse impact parameter with respect to the beamspot (2 mm) largely reduces the contamination from cosmic-ray muons.

A particle-flow (PF) technique [16] is used for the reconstruction of hadronically decaying τ candidates. In the PF approach, information from all subdetectors is combined to reconstruct and identify all final-state particles produced in the collision. The particles are classified as either charged hadrons, neutral hadrons, electrons, muons, or photons. These particles are used to reconstruct τ_h candidates using the hadron plus strip (HPS) algorithm [17], which is designed to optimize the performance of τ_h identification and reconstruction by considering specific τ-lepton decay modes.

4. Signal and background MC samples

Signal and background Monte Carlo (MC) samples are produced with the PYTHIA 6.4.22 [18] and MADGRAPH [19] generators using the Z2 tune [20] and the CTEQL1 parton distribution function (PDF) set [21]. The TAUOLA package [22] is used to decay the generated τ leptons. All generated objects are input into a detailed GEANT4 [23] simulation of the CMS detector.

The Z'_{SSM} and Z'_{ψ} signal samples are generated with seven different masses: 350, 500, 750, 1000, 1250, 1500, and 1750 GeV. Their corresponding cross sections are calculated to leading order.

The most important sources of background are the irreducible Drell–Yan process ($Z \to \tau^+\tau^-$), production of W bosons in association with one or more jets (W + jets), $t\bar{t}$, dibosons (WW, WZ), and QCD multijet production. Although the $Z \to \tau^+\tau^-$ background peaks around the Z mass, its tail extends to the region where a high-mass resonance might present itself. 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 a τ_h. Background from $t\bar{t}$ events is usually accompanied by one or two b jets, in addition to genuine, isolated leptons or τ_h. Background from diboson events produces both genuine, isolated leptons, when the gauge bosons decay leptonically, and a misidentified τ_h when they decay hadronically. Finally, QCD events are characterized by non-collimated jets with a high-multiplicity of particles, which can be misidentified as charged light leptons and τ_h.

Table 1
Lepton p_T, η, and isolation requirements for each $\tau^+\tau^-$ final state.

Selection		$\tau_e\tau_\mu$	$\tau_e\tau_h$	$\tau_\mu\tau_h$	$\tau_h\tau_h$
τ_e	Min p_T (GeV)	15	20	–	–
	Max $|\eta|$	2.1	2.1	–	–
	Iso ΔR	0.3	0.4	–	–
	Max TrkIso (GeV)	3.5	3.0	–	–
	Max EcalIso (GeV)	3.0	4.5	–	–
τ_μ	Min p_T (GeV)	20	–	20	–
	Max $|\eta|$	2.1	–	2.1	–
	Iso ΔR	0.5	–	0.5	–
	Max TrkIso (GeV)	3.5	–	1.0	–
	Max EcalIso (GeV)	3.0	–	1.0	–
τ_h	Min p_T (GeV)	–	20	20	35
	Max $|\eta|$	–	2.1	2.1	2.1
	Iso ΔR	–	0.5	0.5	0.5
	Iso definition	–	Medium	Medium	Loose

5. Event selection

A new heavy neutral gauge boson decaying into τ pairs is characterized by two high-p_T, oppositely charged, isolated, and almost back-to-back (in the transverse plane) τ candidates.

CMS uses a two-level trigger system consisting of the so-called level one (Level-1) and the high-level trigger (HLT). The events selected for this analysis are required to have at least two trigger objects: an electron and a muon, a τ_h candidate and a light charged lepton, or two τ_h candidates for the $\tau_e\tau_\mu$, $\tau_\ell\tau_h$, and $\tau_h\tau_h$ final states, respectively. Details of the electron and muon triggers can be found in Refs. [14,15]. The τ_h trigger algorithm requires the presence of jets reconstructed at Level-1 using a 3×3 combination of calorimeter trigger regions. Those jets are considered as seeds for the HLT where a simplified version of the PF algorithm is used to build the HLT τ_h candidate. The HLT τ_h four-momentum is reconstructed as a sum of the four-momenta of all particles in the jet with p_T above 0.5 GeV in a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around the direction of the leading particle.

The event selection requirements are optimized, for each individual final state, to maximize the sensitivity reach of the search. Events are required to have at least two τ candidates satisfying the p_T, η, and isolation requirements presented in Table 1. The isolation requirement is the strongest discriminator between genuine τ candidates and those from misidentified QCD jets. The leptonic τ candidates (τ_e, τ_μ) are required to pass both track and ECAL isolation requirements. Track isolation (TrkIso) is defined as the sum of the p_T of the tracks, as measured by the tracking system, within an isolation cone of radius ΔR centered around the charged light lepton track. Similarly, ECAL isolation (EcalIso) measures the amount of energy deposited in the ECAL within the isolation cone. In both cases the contribution from the charged light lepton candidate is removed from the sum. For τ_h candidates, the HPS algorithm provides three isolation definitions. The "loose" τ definition rejects a τ candidate if one or more charged hadrons with $p_T \geqslant 1.0$ GeV or one or more photons with transverse energy $E_T \geqslant 1.5$ GeV are found within the isolation cone. The "medium" and "tight" definitions require no charged hadrons or photons with p_T greater than 0.8 and 0.5 GeV within the isolation cone, respectively. Additionally, τ_h candidates are required to fail electron and muon requirements.

Pairs are formed from oppositely charged τ candidates with $\Delta R > 0.7$. In addition, a back-to-back requirement on the τ pairs is imposed by selecting candidates with $\cos\Delta\phi(\tau_1, \tau_2) < -0.95$, where $\Delta\phi(\tau_1, \tau_2)$ is the difference in the azimuthal angle between

Table 2
Signal selection efficiency for Z'_{SSM} decaying into $\tau_e\tau_\mu$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, and $\tau_h\tau_h$ final states.

Z'_{SSM} mass (GeV)	$\tau_e\tau_\mu$	$\tau_e\tau_h$	$\tau_\mu\tau_h$	$\tau_h\tau_h$
350	0.142 ± 0.007	0.050 ± 0.004	0.08 ± 0.01	0.014 ± 0.001
500	0.199 ± 0.008	0.064 ± 0.005	0.13 ± 0.01	0.022 ± 0.001
750	0.257 ± 0.008	0.083 ± 0.007	0.15 ± 0.01	0.030 ± 0.001
1000	0.281 ± 0.009	0.087 ± 0.007	0.17 ± 0.01	0.034 ± 0.001

the τ candidates. The presence of neutrinos in the final state precludes a full reconstruction of the mass of the $\tau^+\tau^-$ system. We use the visible τ-decay products and the missing transverse energy, E_T^{miss}, defined as the magnitude of the negative of the vector sum of the transverse momentum of all PF objects in the event [24], to reconstruct the effective visible mass:

$$M(\tau_1, \tau_2, E_T^{miss}) = \sqrt{\left(E_{\tau_1} + E_{\tau_2} + E_T^{miss}\right)^2 - \left(\vec{p}_{\tau_1} + \vec{p}_{\tau_2} + \vec{E}_T^{miss}\right)^2}. \quad (1)$$

When compared with the mass obtained by using only the visible decay products of the $\tau^+\tau^-$ system, the effective mass provides better discrimination against backgrounds. The width and central value of the effective visible mass distribution, which is offset from the true resonance mass, depend on the true mass of the new resonance. The width-to-mass ratio of the effective mass distribution reconstructed using Eq. (1) varies from ~25% for a Z′ with a generated mass of 350 GeV to ~50% for a Z′ with generated mass of 1750 GeV.

Further selection requirements are applied to suppress background contributions. To discriminate against QCD jets, E_T^{miss} is required to be greater than 20 GeV for the $\tau_e\tau_\mu$ final state and greater than 30 GeV for the $\tau_e\tau_h$, $\tau_\mu\tau_h$, and $\tau_h\tau_h$ final states. Furthermore, we consider only one-prong τ_h candidates in the $\tau_h\tau_h$ final state.

To reduce the contamination from collisions in which W bosons are produced, events are required to be consistent with the signature of a particle decaying into two τ leptons. We define a unit vector ($\hat{\zeta}$) along the bisector defined by the p_T vector of the tau candidates, and two projection variables [25]:

$$p_\zeta^{vis} = \vec{p}_{\tau_1}^{\,vis} \cdot \hat{\zeta} + \vec{p}_{\tau_2}^{\,vis} \cdot \hat{\zeta}, \quad (2)$$

$$p_\zeta = p_\zeta^{vis} + \vec{E}_T^{miss} \cdot \hat{\zeta}. \quad (3)$$

We require that $(1.25 \times p_\zeta^{vis}) - p_\zeta < 10$ GeV for the $\tau_e\tau_\mu$ final state and $(0.875 \times p_\zeta^{vis}) - p_\zeta < 7$ GeV, for the $\tau_\mu\tau_h$, $\tau_e\tau_h$, and $\tau_h\tau_h$ final states. Hereafter, we will refer to the inequalities based on the p_ζ and p_ζ^{vis} variables as the $p_{\hat{\zeta}}$ requirements.

Any remaining contribution from $t\bar{t}$ events is minimized by selecting events where none of the jets has been identified as a b jet. A jet is identified as a b jet if it has at least two tracks with impact parameter significance, defined as the ratio between the impact parameter and its estimated uncertainty, greater than 3.3 [26]. In order to further reduce the $t\bar{t}$ contribution in the $\tau_e\tau_\mu$ final state, an additional requirement is imposed on the difference in the azimuthal angle between the highest-p_T (leading) lepton (ℓ^{lead}) and the E_T^{miss} vector ($\cos\Delta\phi(\ell^{lead}, E_T^{miss}) < -0.6$).

Table 2 summarizes the signal selection efficiency after all requirements have been applied for various Z'_{SSM} masses. The uncertainties in the selection efficiencies are statistical only. The Z'_ψ model has comparable efficiencies.

6. Background estimation

The estimation of the background contributions in the signal region is derived from data wherever possible. The general strategy is to modify the standard selection requirements to select samples enriched with background events. These control regions are used to measure the efficiencies for background candidates to pass the signal selection requirements. In cases where the above approach is not feasible, data-to-MC scale factors, defined as a ratio of efficiencies, are used to correct the expected contributions obtained from the simulation samples.

The number of QCD events in the signal region for the $\tau_h\tau_h$ and $\tau_\ell\tau_h$ final states is estimated from a sample of like-sign $\tau\tau$ candidates scaled by the opposite-sign to like-sign ratio ($R_{OS/LS}$) observed in the data. For the $\tau_h\tau_h$ final state, $R_{OS/LS}$ is measured for events with transverse mass $M_T(\tau_h^{lead}, E_T^{miss})$ between 15 and 90 GeV, where τ_h^{lead} is the highest-p_T τ_h candidate and $M_T(\tau_h^{lead}, E_T^{miss}) = \sqrt{2p_T^{\tau_h^{lead}} E_T^{miss}(1 - \cos\Delta\phi)}$. For the $\tau_\ell\tau_h$ final states $R_{OS/LS}$ is measured from a sample in which the muon TrkIso is between 4 and 15 GeV. For the $\tau_e\tau_\mu$ final state, the QCD background is estimated using a sample of non-isolated electrons and muons. The isolation efficiency, needed to extrapolate into the signal region, is measured from a sample of like-sign candidates.

An enhanced sample of W+jets events is obtained by removing the $\Delta\phi(\tau_1, \tau_2)$ and $p_{\hat{\zeta}}$ requirements from the standard selections. Further enhancement of W events is obtained by requiring that the transverse mass of the lepton and E_T^{miss} system to be between 50 and 100 GeV. The number of W + jets events in the signal region is estimated from the number of events in the W + jets enhanced sample passing the $\Delta\phi(\tau_1, \tau_2)$ and $p_{\hat{\zeta}}$ requirements divided by the efficiency of the transverse mass requirement measured from a sample of events passing the complement of both the $\Delta\phi(\tau_1, \tau_2)$ and $p_{\hat{\zeta}}$ requirements.

A high-purity sample of $t\bar{t}$ events is obtained by requiring the presence of at least one reconstructed b jet with $p_T > 20$ GeV and removing the $\Delta\phi(\tau_1, \tau_2)$ and $p_{\hat{\zeta}}$ requirements. The $t\bar{t}$ contribution in the signal region is estimated from the number of events with one or more b jets passing the $\Delta\phi(\tau_1, \tau_2)$ and $p_{\hat{\zeta}}$ requirements multiplied by the ratio of events passing the zero b-jet requirement and those events with one or more b jets. This ratio is measured from a sample with at least two additional jets in the events, which is dominated by $t\bar{t}$ events.

Control samples dominated by $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ background events are obtained by removing the E_T^{miss} requirement and requiring the τ candidates to be compatible with charged light-lepton signatures. The number of events in each control sample is compared with the expected contributions as determined from the simulation and are found to be in agreement. Since the $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ backgrounds are well described by the simulation, the estimated background contribution from these sources is taken directly from the number of simulated events passing the standard selection requirements normalized to the recorded integrated luminosity and the next-to-next-leading order cross-section value.

The contamination from diboson production is estimated directly from the number of simulated events that pass the analysis requirements normalized to the integrated luminosity with next-to-leading order (NLO) cross-section values.

Table 3
Number of observed events in data and estimated background events for the whole mass range. The first and second uncertainties are the statistical and systematic, respectively.

Process	$\tau_e\tau_\mu$	$\tau_e\tau_h$	$\tau_\mu\tau_h$	$\tau_h\tau_h$
$Z \to \tau^+\tau^-$	$816 \pm 58 \pm 44$	$462 \pm 56 \pm 24$	$804 \pm 53 \pm 44$	$30.9 \pm 3.6 \pm 4.3$
$Z \to \mu^+\mu^-$	–	–	$20.8 \pm 8.3 \pm 1.1$	–
$Z \to e^+e^-$	–	$220 \pm 24 \pm 11$	–	$0.66 \pm 0.33 \pm 0.22$
W + jets	$83 \pm 15 \pm 7$	$181 \pm 36 \pm 13$	$459 \pm 26 \pm 29$	$5.8 \pm 1.7 \pm 1.1$
WW	$55.6 \pm 1.4 \pm 1.9$	–	$24.59 \pm 0.80 \pm 0.80$	–
WZ	$5.60 \pm 0.35 \pm 0.22$	–	–	–
$t\bar{t}$	$9.6 \pm 1.2 \pm 0.7$	$10.8 \pm 2.8 \pm 0.9$	$46.2 \pm 6.9 \pm 3.7$	$0.00^{+0.76+0.15}_{-0.00}$
QCD	$45.1 \pm 3.3 \pm 9.0$	$185 \pm 31 \pm 19$	$72 \pm 18 \pm 8$	$467 \pm 26 \pm 67$
Total	$1015 \pm 60 \pm 45$	$1058 \pm 77 \pm 35$	$1427 \pm 63 \pm 53$	$504 \pm 26 \pm 67$
Observed	1044	1043	1422	488

Table 4
Number of observed events in data and estimated background events obtained from the integration of the $M(\tau_1, \tau_2, E_T^{miss})$ distribution for masses above 300 GeV. The statistical and systematic uncertainties have been added in quadrature.

Process	$\tau_e\tau_\mu$	$\tau_e\tau_h$	$\tau_\mu\tau_h$	$\tau_h\tau_h$
$Z \to \tau^+\tau^-$	2.76 ± 0.25	12.5 ± 1.7	18.0 ± 1.5	3.41 ± 0.62
$Z \to \mu^+\mu^-$	–	–	3.0 ± 1.2	–
$Z \to e^+e^-$	–	6.94 ± 0.83	–	–
W + jets	4.86 ± 0.97	0.23 ± 0.05	9.58 ± 0.81	1.83 ± 0.69
WW	8.53 ± 0.36	–	4.01 ± 0.18	–
WZ	1.34 ± 0.10	–	–	–
$t\bar{t}$	1.57 ± 0.23	0.93 ± 0.25	6.6 ± 1.1	–
QCD	–	0.13 ± 0.03	0.16 ± 0.04	18.0 ± 2.9
Total	19.1 ± 1.1	20.8 ± 1.9	41.3 ± 2.4	23.3 ± 3.0
Observed	20	10	32	13

Finally, high-purity samples of $Z \to \tau_\ell\tau_h$ events in which the data-to-MC scale factor can be evaluated are obtained by removing the E_T^{miss} selection and requiring that the τ_ℓ transverse momentum be less than 40 GeV. Contamination from W + jets events in these samples is reduced after requiring $M_T(\tau_\ell, E_T^{miss}) < 40$ GeV. For the $\tau_e\tau_\mu$ final state the data-to-MC scale factor is evaluated for $M(\tau_e, \tau_\mu, E_T^{miss}) < 150$ GeV.

Table 3 lists the number of estimated background events compared with the total number of observed events in data for each final state. The statistical and systematic uncertainties are quoted separately. Only the uncertainties on the cross section and background estimation methods are included in the systematic uncertainties. Other effects, such as the uncertainty of the luminosity measurement, are not included in Table 3. The $\tau^+\tau^-$ effective visible mass distributions, $M(\tau_1, \tau_2, E_T^{miss})$, for all four final states are shown in Fig. 1. The largest background sources are from W + jet(s) and Drell–Yan production for $\tau_e\tau_\mu$ and $\tau_\ell\tau_h$ final states, and QCD processes for $\tau_h\tau_h$. We use the background shapes normalized to the values obtained from the background estimation methods to search for a broad enhancement in the $M(\tau_1, \tau_2, E_T^{miss})$ spectrum consistent with the production of a high-mass resonance state. The background shapes are taken from the MC simulation and parametrized to extrapolate to the high-mass regions. Table 4 lists the number of observed events in data and the estimated background contributions for events with $M(\tau_1, \tau_2, E_T^{miss}) > 300$ GeV.

7. Systematic uncertainties

The main source of systematic uncertainty results from the estimation of the background contributions that are dominated by the statistical uncertainty of the data used in the control regions. These uncertainties are in the range of 6 to 14%. The contamination from other backgrounds in these control regions has a negligible effect on the systematic uncertainty. The efficiencies for electron and muon reconstruction and identification are measured with the "tag-and-probe" method [14,15] with a resulting uncertainty of 4.5% for electrons and up to 3% for muons. The hadronic τ trigger efficiency is measured from $Z \to \tau_\mu\tau_h$ events selected by single-muon triggers. This leads to a relative uncertainty of 4.0% and 6.4% per τ_h candidate for the $\tau_\ell\tau_h$ and $\tau_h\tau_h$ final states, respectively. Systematic effects associated with τ_h identification are extracted from a fit to the $Z \to \tau^+\tau^-$ visible mass distribution, $M(\tau_1, \tau_2)$. The fit constrains the Z production cross section to the measured cross section in $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ decay channels, leading to a relative uncertainty of 6.8% per τ_h candidate [27]. The simulation is used to verify that τ_h identification efficiency remains constant as a function of p_T up to the high-mass signal region.

Uncertainties that contribute to the $M(\tau_1, \tau_2, E_T^{miss})$ shape variations include the τ_h (2%) and charged light-lepton (1%) energy scales, and the uncertainty on the E_T^{miss} scale, which is used for the $M(\tau_1, \tau_2, E_T^{miss})$ mass calculation. The E_T^{miss} scale uncertainties contribute via the jet energy scale (2–5% depending on η and p_T) and unclustered energy scale (10%), where unclustered energy is defined as the energy not associated with the reconstructed leptons and jets with $p_T > 10$ GeV. The unclustered energy scale uncertainty has a negligible systematic effect on the signal acceptance and $M(\tau_1, \tau_2, E_T^{miss})$ shape. In addition, the limited sizes of the simulated samples in the high-mass regions lead to systematic uncertainties in the background shape parametrization at high mass. The uncertainty on the probability for a light quark or gluon jet to be misidentified as a b jet (20%) also has a negligible effect on the signal acceptance and $M(\tau_1, \tau_2, E_T^{miss})$ mass shape.

The uncertainty on signal acceptance due to the PDF set included in the simulated samples is evaluated by comparing CTEQ6.6L, MRST2006, and NNPDF10 PDF sets [28–30] with the default PDF set. The systematic effect due to imprecise modeling of initial- and final-state radiation is determined by reweighting events to account for effects such as missing α terms in the soft-collinear approach [31] and missing NLO terms in the parton shower approach [32]. Finally, the uncertainty in the luminosity measurement is 2.2% [33]. Table 5 summarizes the sources of systematics considered.

8. Results

The observed mass spectra shown in Fig. 1 do not reveal any evidence for $Z' \to \tau^+\tau^-$ production. A fit of the expected mass spectrum to the data based on the CL_S criterion [34,35] is used to calculate an upper limit on the product of the resonance cross section and its branching fraction into τ-lepton pairs at 95% CL as a function of the Z' mass for each $\tau^+\tau^-$ final state taking into account all systematic uncertainties shown in Table 5. The final limits are obtained from the combination of all four final states.

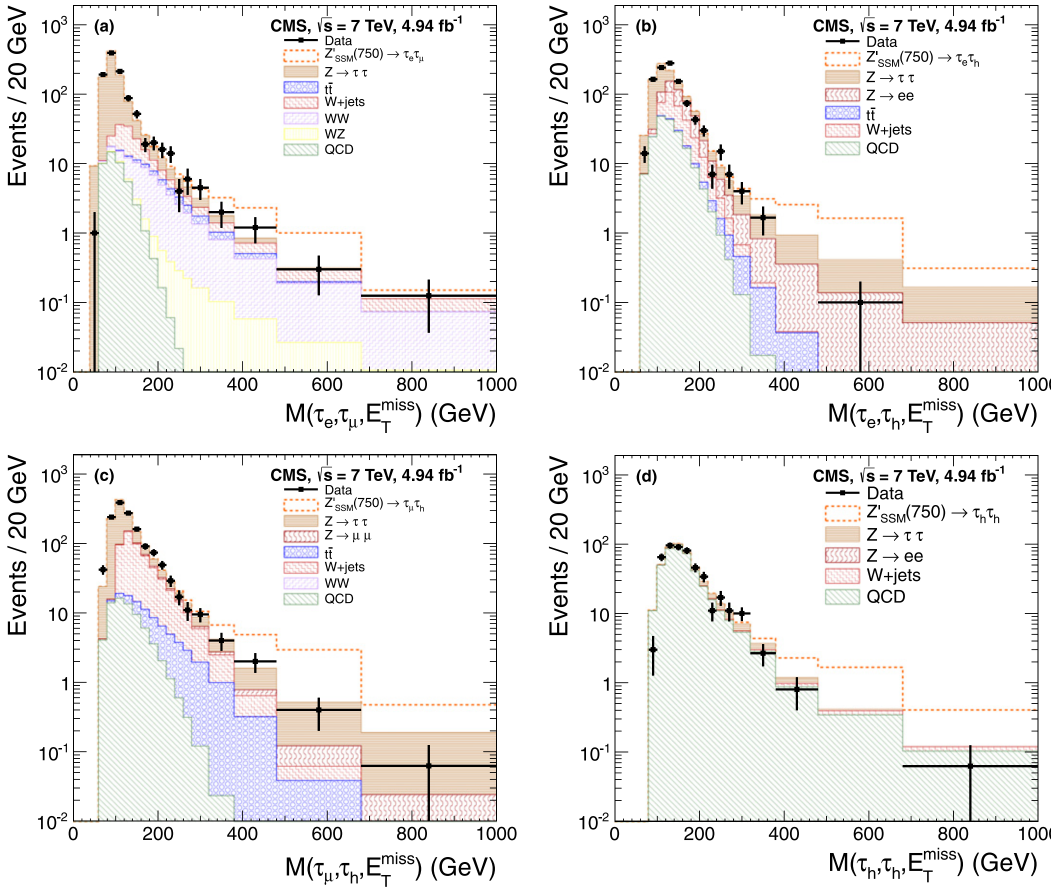

Fig. 1. $M(\tau_1, \tau_2, E_T^{miss})$ distributions for all four final states: (a) $\tau_e\tau_\mu$, (b) $\tau_e\tau_h$, (c) $\tau_\mu\tau_h$, and (d) $\tau_h\tau_h$. The dashed line represents the mass distribution for a $Z'_{SSM} \to \tau^+\tau^-$ with a mass of 750 GeV.

Table 5
Summary of the sources of systematic uncertainties.

Source of systematic	$\tau_e\tau_\mu$	$\tau_e\tau_h$	$\tau_\mu\tau_h$	$\tau_h\tau_h$
Background estimation	7.4%	8.0%	5.8%	14.3%
Muon id	3.0%	–	1.1%	–
Electron id	4.5%	4.5%	–	–
Tau id	–	6.8%	6.8%	9.6%
Tau energy scale	–	2.1%	2.1%	3.0%
Tau trigger	–	4.0%	4.0%	9.0%
Jet energy scale			4.0%	
Luminosity			2.2%	
Parton distribution functions			4.0–6.5%	
Initial-state radiation			3.1%	
Final-state radiation			2.2%	

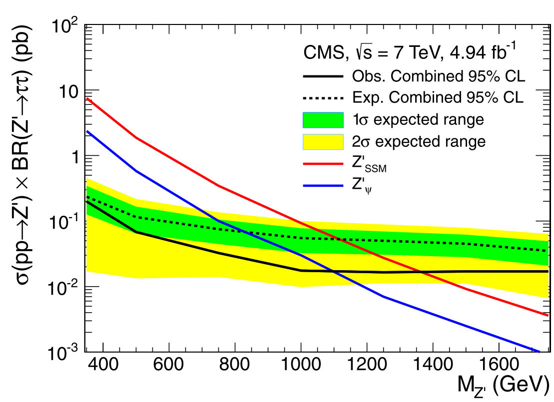

Fig. 2. Combined upper limit at the 95% CL on the product of the cross section and branching fraction into τ pairs as a function of the Z' mass. The bands represent the one and two standard deviations obtained from the background-only hypothesis.

Fig. 2 shows the combined expected and observed limits as well as the theoretical cross section times the branching fraction to τ-lepton pairs for the SSM (Z'_{SSM}) and E_6 (Z'_ψ) models as functions of the Z' resonance mass. The bands on the expected limits represent the one and two standard deviations obtained using a large sample of pseudo-experiments based on the background-only hypothesis. The upper limit on $\sigma(pp \to Z') \times Br(Z' \to \tau^+\tau^-)$ corresponds to the point where the observed limit crosses the theoretical line. We exclude a Z'_{SSM} with mass below 1.4 TeV and a Z'_ψ with mass less than 1.1 TeV. The $\tau_e\tau_h$ and $\tau_\mu\tau_h$ final states contribute the most to the limits. A downward fluctuation in the number of observed events with respect to the number of expected events leads to a limit that is about 1.5 standard deviations higher than expected in the region above 600 GeV.

9. Summary

A search for new heavy Z' bosons decaying into τ-lepton pairs using data corresponding to an integrated luminosity of $4.94 \pm 0.11\ fb^{-1}$ collected by the CMS detector in proton–proton collisions at $\sqrt{s} = 7$ TeV was performed. The observed mass spectrum did not reveal any evidence for $Z' \to \tau^+\tau^-$ production, and an upper limit, as a function of the Z' mass, on the product of the resonance cross section and branching fraction into $\tau^+\tau^-$ was calculated. The Z'_{SSM} and Z'_ψ resonances decaying to τ-lepton pairs were excluded for masses below 1.4 and 1.1 TeV, respectively, at

95% CL. These represent the most stringent limits on the production of a new heavy resonance decaying into τ-lepton pairs published to date.

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