EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2018-202
2018/07/31

CMS-EXO-17-008

Search for a W′ boson decaying to a τ lepton and a neutrino in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search for a new high-mass resonance decaying to a tau lepton and a neutrino is reported. The analysis uses proton-proton collision data collected by the CMS experiment at the LHC at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $35.9\,\text{fb}^{-1}$. The search utilizes hadronically decaying tau leptons. No excess in the event yield is observed at high transverse masses of the τ and missing transverse momentum. An interpretation of results within the sequential standard model excludes W′ boson masses below 4.0 TeV at 95% confidence level. Existing limits are also improved on models in which the W′ boson decays preferentially to fermions of the third generation. Heavy W′ bosons with masses less than 1.7–3.9 TeV, depending on the coupling in the non-universal G(221) model, are excluded at 95% confidence level. These are the most stringent limits on this model to date.

Submitted to Physics Letters B

*See Appendix A for the list of collaboration members

1 Introduction

New charged heavy gauge bosons, generally referred to as W′ bosons, are predicted by various extensions of the standard model (SM). An example is the sequential standard model (SSM) [1], featuring an extended gauge sector, which is often used as a benchmark model. Lepton universality holds in the SSM; however, there exist models without this assumption. Nonuniversal gauge interaction models (NUGIMs) [2–6] predict an enhanced W′ boson branching fraction to the third generation fermions. In this approach, the high top quark mass is associated with the large vacuum expectation value of the corresponding Higgs field.

The analysis presented in this Letter searches for $W' \to \tau\nu$ events, where the τ lepton decays hadronically. The leading order Feynman diagram is shown in Fig. 1. In this Letter, the symbol τ_h will be used to denote the visible part of the hadronic decay of the tau, which is reconstructed as a tau jet in the detector. The hadronic decays of the tau lepton are experimentally distinctive because they result in low charged-hadron multiplicity, unlike jets originating from the hadronization of partons produced in the hard scattering process, which have high charged-hadron multiplicity. The signature of a W′ boson event is similar to that of a W boson event in which the W boson is produced "off-shell" with a high mass.

Searches for a W′ boson decaying to a τ lepton and a neutrino have been performed previously by the CMS [7] and ATLAS [8] collaborations at the CERN LHC. Searches for a W′ boson have been performed also in $e + p_T^{miss}$, $\mu + p_T^{miss}$ [9], WZ [10], qq′ [11] and tb [12] channels. The ATLAS experiment has excluded an SSM W′ for masses below 3.7 TeV in the $\tau_h + p_T^{miss}$ channel. The CMS experiment has excluded an SSM W′ for masses below 5.2 TeV in the combination of electron and muon channels. This Letter describes a search for a W′ boson in the $\tau_h + p_T^{miss}$ channel using proton-proton (pp) collisions collected in 2016 at a center-of-mass energy of 13 TeV. The data set corresponds to an integrated luminosity of 35.9 fb^{-1}. The results are interpreted in the context of two models, the SSM and the NUGIM.

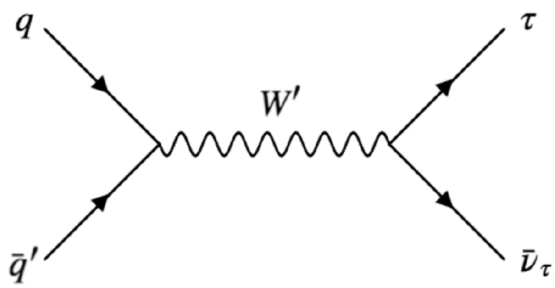

Figure 1: Leading order Feynman diagram of the expected signal process $W' \to \tau\nu$.

2 Physics models

2.1 The sequential standard model W′ boson

In the SSM, the W′ boson is a heavy analog of the W boson. It is a resonance with fermionic decay modes and branching fractions similar to those of the SM W boson, with the addition of the decay $W' \to tb$, which becomes relevant for W′ boson masses larger than 180 GeV. If the W′ boson is heavy enough to decay to top and bottom quarks, the SSM branching fraction for the decay $W' \to \tau\nu$ is 8.5% [1]. Under these assumptions, the relative width Γ/M of the W′ boson is ∼3.3%. Decays into WZ depend on the specific model assumptions and are usually considered to be suppressed in the SSM, as assumed by the current search.

In accordance with previous analyses, it is assumed that there is no interference between the production of the new particle and the production of the SM W boson. Such an absence of interference would occur, for example, if the W′ interacts via V+A coupling [13].

Signal events for the SSM W′ boson are simulated at leading order (LO) with PYTHIA 8.212 [14], using the NNPDF 2.3 [15, 16] parton distribution function (PDF) set and tune CUETP8M1 [17]. The W′ samples are normalized to next-to-next-to-leading-order (NNLO) cross sections from FEWZ [18, 19].

2.2 Coupling strength

The W′ boson coupling strength, $g_{W'}$, is given in terms of the SM weak coupling strength $g_W = e/\sin^2\theta_W \approx 0.65$. Here, θ_W is the weak mixing angle. If the W′ is a heavier copy of the SM W boson, their coupling ratio is $g_{W'}/g_W = 1$ and the SSM W′ theoretical cross sections, signal shapes, and widths apply. However, different couplings are possible. Because of the dependence of the width of a particle on its coupling, and the consequent effect on the transverse mass distribution, a limit can also be set on the coupling strength. For this study, a reweighting procedure is used. Some selected signal samples are simulated at LO with MADGRAPH (version 1.5.11) [20], for a range of coupling ratios $g_{W'}/g_W$ from 0.01 to 3. These signals exhibit different widths as well as different cross sections. The generated distributions of the SSM PYTHIA samples with $g_{W'}/g_W = 1$ are reweighted to take into account the decay width dependence, thus providing the appropriate reconstructed transverse mass distributions for $g_{W'}/g_W \neq 1$. For $g_{W'}/g_W = 1$, the theoretical LO cross sections apply and this coupling strength is used to compare the standard SSM samples with the reweighted ones, allowing the reweighting method to be verified.

2.3 Nonuniversal gauge interaction model

Models with nonuniversal couplings predict an enhanced branching fraction for the third generation of fermions and explain the large mass of the top quark. The nonuniversal gauge interaction models (NUGIMs) exhibit a $SU(2)_l \times SU(2)_h \times U(1)$ symmetry, and thus are often called G(221) models. Here the indices l and h refer to light and heavy, respectively. The weak SM $SU(2)_W$ group is a low-energy limit of two gauge groups, a light $SU(2)_l$ and a heavy $SU(2)_h$, which govern the couplings to the light fermions of the first two generations and to the heavy fermions of the third generation, respectively. These two groups mix, resulting in an SM-like $SU(2)_W$ and an extended group $SU(2)_E$. The $SU(2)_E$ extended gauge group gives rise to additional gauge bosons such as a W′. The mixing of the two gauge groups involves a mixing angle of the extended group, θ_E, which modifies the couplings to the heavy boson. Consequently, the mixing modifies the production cross section and, as illustrated in Fig. 2, the branching fractions of the W′. For $\cot\theta_E \gtrsim 3$ the W′ decays predominantly to third generation fermions. The branching fraction to WH is smaller than the branching fraction to third generation fermions, as shown in Fig. 2. For $\cot\theta_E = 1$ the branching fractions are the same as those of the SSM, and the W′ boson couples democratically to all fermions. For $\cot\theta_E < 1$ the decays into light fermions are dominant.

In the NUGIM G(221), the ratio of the couplings $g_{W'}/g_W$ is related to the parameter $\cot\theta_E$ by the following equation [22]:

$$\Gamma_{W'} = \Gamma_{W'}^{SSM} \frac{(4 + \frac{1}{4})\cot^2\theta_E + 8\tan^2\theta_E}{12 + \frac{1}{4}} = \Gamma_{W'}^{SSM} \left(\frac{g_{W'}}{g_W}\right)^2 \tag{1}$$

Because of this functional relationship, a reinterpretation of limits on coupling strength will

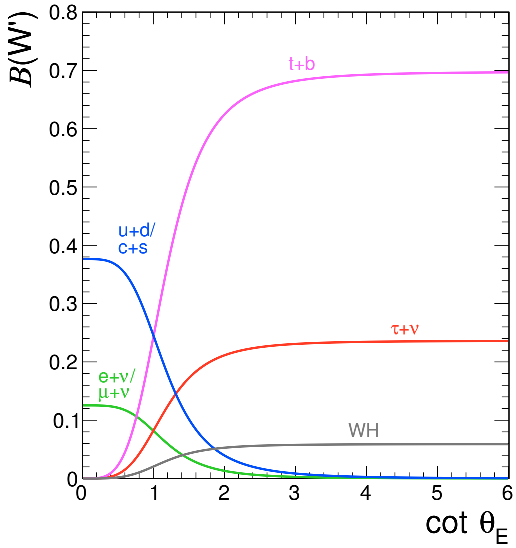

Figure 2: Branching fractions $\mathcal{B}(\mathrm{W}')$ as a function of the mixing angle $\cot\theta_\mathrm{E}$, for W' boson decays in the NUGIM G(221) framework, as calculated in Refs. [2, 21, 22]. For $\cot\theta_\mathrm{E} = 1$ the values correspond to those in the SSM, rescaled to accommodate the WH decay channel.

yield limits on NUGIM G(221), and thus it was not necessary to generate a signal sample for this model.

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 (HCAL), 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 detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measures charged particles within the range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules. For nonisolated particles with transverse momentum $1 < p_\mathrm{T} < 10\,\mathrm{GeV}$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 μm in the transverse impact parameter and 45–150 μm in the longitudinal impact parameter. The ECAL consists of 75 848 lead tungstate crystals, which provide coverage of $|\eta| < 1.48$ in a barrel region (EB) and $1.48 < |\eta| < 3.0$ in two endcap regions (EE). The HCAL is a sampling calorimeter, which utilizes alternating layers of brass as an absorber and plastic scintillator as active material, covering the range $|\eta| < 3$. In the forward region, the calorimetric coverage is extended to $|\eta| < 5$ by a steel and quartz fiber Cherenkov hadron forward calorimeter. Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Events of interest are selected using a two-tiered trigger system [23].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [24].

4 Background simulation

The dominant SM background is the production of W+jets. This background is generated at LO using MADGRAPH5_aMC@NLO version 2.2.2 with the MLM merging [20, 25] and the NNPDF 3.0 [15, 16, 26] PDF set for on-shell W boson production and using PYTHIA 8.212 with the NNPDF 2.3 PDF set for off-shell production. The differential cross section is reweighted as a function of the invariant mass of the SM W boson decay products, incorporating NNLO quantum chromodynamics (QCD) and next-to-leading-order (NLO) electroweak corrections. The effect with respect to the LO calculation corresponds to a correction factor (K factor) for the W boson transverse mass spectrum, which is calculated as the additive combination of the higher-order effects. The K factor is 1.15 at a W′ mass of 0.3 TeV and drops monotonically for higher masses down to 0.6 for a mass of 6 TeV. The calculation uses the generators FEWZ 3.1 and MCSANC 1.01 [27] for the QCD and electroweak corrections, following the recommended combination from Ref. [28].

The difference between the K factors obtained with additive and multiplicative combination is considered as the uncertainty in the K factors of the W+jets background.

Other background processes are: $Z/\gamma* \to \ell\ell$ generated with MADGRAPH5_aMC@NLO version 2.3.2.2 [20] with the NNPDF 3.0 PDF set, diboson processes generated with PYTHIA 8.212 and with the NNPDF 2.3 PDF set, and top quark processes generated with POWHEG 2.0 [29–34] and the NNPDF 3.0 PDF set. Background from jets that are falsely identified as τ_h candidates is dominated by $Z \to \nu\nu +$ jets events, which are simulated with MADGRAPH5_aMC@NLO version 2.3.2.2 and with the NNPDF 3.0 PDF set.

Parton fragmentation and hadronization are performed with PYTHIA 8.212 with the underlying event tune CUETP8M1. The detector response is simulated using a detailed description of the CMS detector implemented with the GEANT4 package [35]. All simulated event samples are normalized to the integrated luminosity of the recorded data, using the theoretical cross section values. Additional pp collisions during the same bunch crossing (pileup) is taken into account by superimposing simulated minimum bias interactions onto all simulated events. The simulated events are weighted so that the pileup distribution matches that of the data, with an average of about 27 interactions per bunch crossing.

5 Reconstruction and identification of physics objects

A particle-flow (PF) algorithm [36] 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, missing transverse momentum (p_T^{miss}), and jets. The vector $\vec{p}_T^{miss}$ is defined as the negative vector p_T sum of all PF candidates reconstructed in the event. The magnitude of this vector is referred to as p_T^{miss}. The raw p_T^{miss} value is modified to account for corrections to the energy scale of all the reconstructed jets in the event [37]. The jets are clustered using the anti-k_T jet finding algorithm [38, 39]. The reconstructed vertex with the largest value of summed physics-object p_T^2 is taken as the primary vertex.

Electrons [40, 41] are reconstructed by matching energy deposits in the ECAL with track segments in the inner tracker. Muon reconstruction [42] is performed by matching a track segment reconstructed in the inner tracker with a track segment reconstructed in the muon detector and performing a global fit of the charge deposits from the two track segments.

The τ_h reconstruction in CMS starts from jets clustered from PF candidates, using the anti-

k_T algorithm with a distance parameter of 0.4. The τ_h candidates are reconstructed using the hadrons-plus-strips algorithm [43, 44], which is designed to optimize the performance of τ_h reconstruction and identification by considering specific τ lepton decay modes. Individual τ_h decay modes are reconstructed separately. The signatures distinguished by the algorithm are: a single charged hadron, a charged hadron and up to two neutral pions, and three charged hadrons.

Requiring τ_h candidates to pass isolation requirements reduces the jet $\to \tau_h$ misidentification probability. The multivariant-based (MVA-based) τ_h identification discriminant combine isolation and other variables with sensitivity to the τ lifetime, to provide the best possible discrimination for τ_h decays against quark and gluon jets. Hadronically decaying τ leptons in this analysis are required to satisfy the very loose working point of the MVA-based isolation [45]. This working point has an efficiency of about 70% for genuine τ_h, with about 0.4% misidentification rate for quark- and gluon-initiated jets, for a p_T range typical of τ_h originating from a W′ boson of mass of 2 TeV. Isolated electrons have a high probability to be misidentified as τ_h objects that decay to a single charged hadron ($h^\pm$ or $h^\pm\pi^0$). Electrons can emit energetic bremsstrahlung photons as they traverse the material of the silicon tracker. When this occurs, the electron and accompanying photons may be mistakenly reconstructed as a hadronically decaying tau. Muons can also be reconstructed as τ_h objects in the $h^\pm$ decay mode. The τ_h candidates in this analysis are further required to pass antilepton discriminators that reduce the number of electrons and muons misidentified as τ_h candidates [45].

6 Analysis strategy

The discriminating variable used in this analysis is the transverse mass, defined as follows:

$$m_T = \sqrt{2 p_T^\tau p_T^{miss} [1 - \cos\Delta\phi(\vec{p}_T^{\,\tau}, \vec{p}_T^{\,miss})]}, \tag{2}$$

where p_T^τ is the magnitude of the transverse momentum vector of the τ_h candidate $\vec{p}_T^{\,\tau}$, and $\Delta\phi$ is the difference in the azimuthal angle between $\vec{p}_T^{\,\tau}$ and $\vec{p}_T^{\,miss}$.

The strategy of this analysis is to select a heavy boson candidate decaying almost at rest to a hadronic jet consistent with a τ_h candidate and neutrinos, the latter manifesting themselves as p_T^{miss}. Signal events are selected online with a $\tau_h + p_T^{miss}$ trigger that requires the p_T of the τ_h candidate to be greater than 50 GeV and the value of p_T^{miss} to be greater than 90 GeV. To ensure that the trigger is maximally efficient for selected events, the offline selection requires one isolated τ_h candidate to have p_T^τ greater than 80 GeV and p_T^{miss} to be greater than 200 GeV.

Although there are two neutrinos in the final state, p_T^{miss} and the isolated τ_h candidate are largely produced in opposite directions, which helps to distinguish signal from background events especially those coming from QCD multijet production. Two selection criteria exploit this behavior to reduce the background: the ratio of the p_T^τ to p_T^{miss} is required to satisfy $0.7 < p_T^\tau / p_T^{miss} < 1.3$; and the angle $\Delta\phi(\vec{p}_T^{\,\tau}, \vec{p}_T^{\,miss})$ has to be greater than 2.4 radians. Consequently, the lowest m_T value is about 300 GeV. To avoid an overlap with the W′ boson search in the electron channel, events are rejected if they contain a loosely identified electron with $p_T > 20$ GeV and $|\eta| < 2.5$, where the loose working point is $\approx$ 90% efficient for real electrons. For similar reasons, events containing a loosely identified muon with $p_T > 20$ GeV and $|\eta| < 2.4$ are not considered in this analysis, where the loose working point is >99% efficient for real muons.

After all selections, the m_T distributions for the observed data and expected background events are presented in Fig. 3 (left). Figure 3 (right) shows the integral distribution, which is formed by

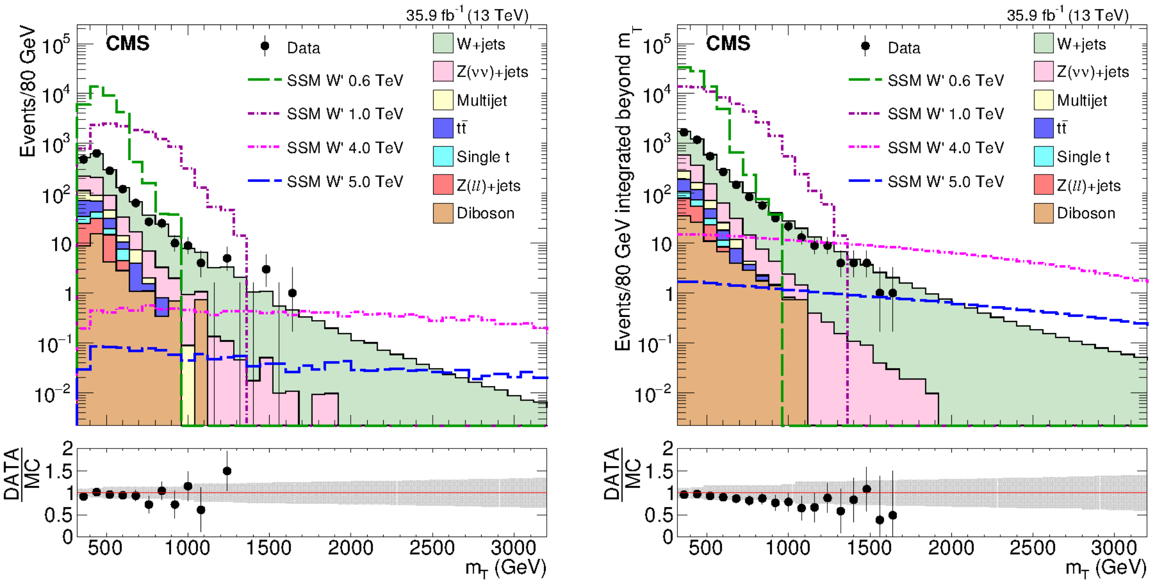

Figure 3: (Left) The m_{T} distribution after the final selection. The black symbols with error bars show data, while the filled histograms represent the SM backgrounds. Signal examples for SSM W′ bosons with masses of 0.6, 1.0, 4.0, and 5.0 TeV are shown with the open histograms. (Right) The integral transverse mass distribution, where the value in each bin is equal to the number of events with transverse mass equal to or greater than the left of the bin. The lower panels show the ratio of data to prediction, and the gray band represents the systematic uncertainties.

filling each bin of the histogram with the sum of that bin and all following bins. The systematic uncertainties, which are detailed in Section 7, are illustrated as a grey band in the lower panels of the plots. The product of the signal efficiency and acceptance for SSM W′ $\rightarrow \tau\nu$ events depends on the W′ boson mass. The total signal efficiency for the studied range of $m_{\mathrm{T}} >$ 300 GeV varies from 14% to about 24% as $M_{\mathrm{W'}}$ increases from 1 to 3 TeV. For higher W′ boson masses, events shift to lower m_{T} because of the increasing fraction of off-shell production (as shown in Fig. 3 for a few signal mass points). For example, for a W′ boson with a mass of 5 TeV, the total signal efficiency is around 17%. Within a ±25% mass range around the $M_{\mathrm{W'}}$ the efficiency of an SSM W′ is around 5% for $M_{\mathrm{W'}} = 1$ TeV, 5% for $M_{\mathrm{W'}} = 3$ TeV, and 2% for $M_{\mathrm{W'}} = 5$ TeV. The trigger threshold affects the signal efficiency in the low-mass range. These efficiency values are obtained assuming the W′ $\rightarrow \tau\nu$ branching fraction to be unity. The efficiency values are estimated using simulated events where the τ lepton decays hadronically.

The dominant background is from the off-shell tail of the m_{T} distribution of the SM W boson, and is obtained from simulation. The background contributions from $\mathrm{Z}(\rightarrow \nu\nu) +$jets and QCD multijet events are also obtained from simulation. These backgrounds primarily arise as a consequence of jets misidentified as τ_{h} candidates. The contribution of QCD multijet background is small compared to $\mathrm{Z}(\rightarrow \nu\nu) +$jets in the signal region. Following the strategy in Ref. [46], to ensure that the misidentified tau background is simulated properly, the agreement between data and simulation is checked in a control region dominated by $\mathrm{Z}(\rightarrow \mu\mu) +$jets events, where a jet is misidentified as a τ_{h} candidate. The $p_{\mathrm{T}}^{\mathrm{miss}}$ is recalculated excluding the muons from the Z decay in order to reproduce the $p_{\mathrm{T}}^{\mathrm{miss}}$ distribution of $\mathrm{Z} \rightarrow \nu\nu$ events. Specifically, the control region is defined as follows. Events are selected online using a dimuon trigger with muon p_{T} thresholds of 17 and 8 GeV. They must contain two oppositely charged muons with

$p_T > 20\,\text{GeV}$ and $|\eta| < 2.4$, both passing loose identification and isolation requirements. The invariant mass of the dimuon system is required to be between 81 and 101 GeV. In addition, the events are required to contain exactly one τ_h candidate passing the same selection requirements as in the signal region, with $p_T^\tau > 20\,\text{GeV}$ and $|\eta^\tau| < 2.1$. To remove the overlap between muon and τ_h candidates, the separation between them must fulfill $\Delta R(\mu, \tau_h) > 0.1$, where ΔR is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Data and simulation are compared using distributions of the dimuon mass, p_T^{miss}, p_T/p_T^{miss}, m_T, η^τ and p_T^τ. Figure 4 shows the p_T^τ distribution in the control region. Data and simulation agree within 50% in all bins except in one bin in the tail of

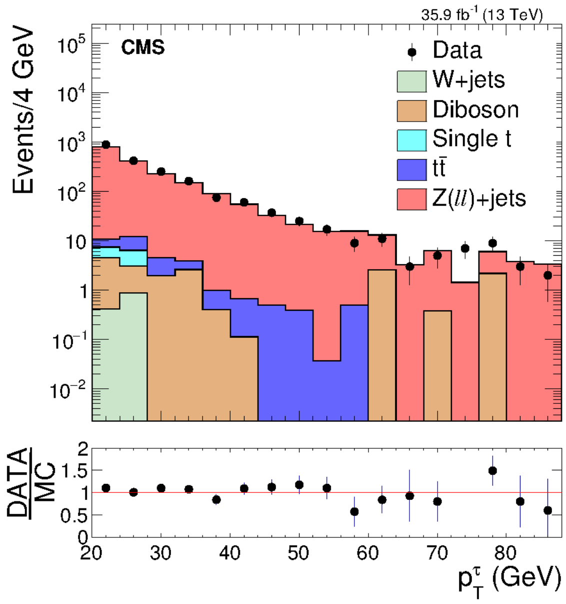

Figure 4: Distribution of p_T^τ in the control region. The black symbols with error bars show the data, while the histograms represent the SM backgrounds. The lower panel shows the ratio of data to prediction.

the p_T^τ distribution, giving confidence that the misidentified τ_h background source—about 22% of the total background—is correctly modeled in the simulation.

7 Systematic uncertainties

The uncertainty in the modeling of the m_T distribution can be split into three categories: uncertainties affecting shape and normalization, uncertainties affecting only normalization and an uncertainty due to limited numbers of events in simulated samples.

The dominant uncertainty of the first category comes from τ_h reconstruction and identification, affecting background and a potential signal in the same way. The uncertainty associated with the τ_h identification is 5% [43]. An additional systematic uncertainty, which dominates for high-p_T τ_h candidates, is related to the degree of confidence that the MC simulation correctly models the identification efficiency. This additional uncertainty increases linearly with p_T^τ and amounts to $+5\%/-35\%$ at $p_T^\tau = 1\,\text{TeV}$. The uncertainty is asymmetric because studies indicate that the tau identification efficiency is smaller in data than in simulation, and the difference increases as the p_T of the tau increases. The uncertainty in the τ_h energy scale amounts to 3% [43]. The main sources of p_T^{miss} uncertainty from jets are the jet energy scale and jet energy resolution [47].

For the energy measurements of other objects the following uncertainties are applied: 3% [43] for τ_{h}, 0.6% in EB and 1.5% in EE, respectively, for electrons and photons [48]; and 0.2% for muons [42]. The contribution to the uncertainty in $p_{\mathrm{T}}^{\mathrm{miss}}$ associated with unclustered energy is estimated by varying this energy by $\pm$10%. For the tau plus $p_{\mathrm{T}}^{\mathrm{miss}}$ trigger, a scale factor of 0.9 is applied. The scale factor has an uncertainty of 10%. The uncertainty associated with the choice of the PDF in the simulation is evaluated according to the PDF4LHC prescription [49–51]. The values increase with m_{T}, ranging from an uncertainty of 1 to 10% at $m_{\mathrm{T}} = 0.5$ to 4.0 TeV. For the K factor of the W boson background, the difference between additive and multiplicative combination, which is around 5%, is taken to be the systematic uncertainty. The simulated events are weighted so that the pileup distribution matches the measured one, using a value for the total inelastic cross section of 69.2 mb, which has an uncertainty of $\pm$4.6% [52].

Uncertainties of the second category influence only the normalization of the m_{T} distribution. Kinematic distributions in the $\mathrm{Z}(\rightarrow \mu\mu) + \mathrm{jets}$ control region demonstrate that data and simulation agree within 50% for misidentified τ_{h} background, which is composed of $\mathrm{Z}(\rightarrow \nu\nu) + \mathrm{jets}$ and QCD multijet events. This guides the assignment of a 50% systematic uncertainty in the normalization of these backgrounds. The uncertainty in the electron identification efficiency (veto) is 2% and the uncertainty in the integrated luminosity measurement is 2.5% [53].

Uncertainties in the third category arise from limited sizes of event samples in the simulation of background processes. In contrast to all other uncertainties, they are not correlated between the bins of the invariant mass distribution.

In the high-mass region, where both the expected and the observed numbers of events are consistent with zero, the effect of the systematic uncertainty on the exclusion limits is negligible.

The relevant systematic uncertainties taken into account in the estimation of potential signals include those associated with τ_{h} identification and energy scale, $p_{\mathrm{T}}^{\mathrm{miss}}$, trigger, pile-up simulation, and integrated luminosity. The uncertainty in the signal K factor arises from the choices of PDF and α_S. The combined uncertainty is evaluated using the PDF4LHC prescription, where in the computation of each PDF set, the strong coupling constant is varied. Uncertainties from different PDF sets and α_S variation are added in quadrature.

8 Results

The transverse mass distribution in Fig. 3 shows no significant deviations from the expected SM background. Signal events are expected to be particularly prominent at the upper end of the m_{T} distribution, where the expected SM background is low. The expected and measured yields are summarized in Table 1 together with the detailed systematic uncertainties described in Section 7.

8.1 Statistical analysis

Upper limits on the product of the production cross section and branching fraction, $\sigma(\mathrm{pp} \rightarrow \mathrm{W}')\mathcal{B}(\mathrm{W}' \rightarrow \tau\nu)$, are determined using a Bayesian method [54] with a uniform positive prior probability distribution for the signal cross section. All limits presented here are at 95% confidence level (CL). The nuisance parameters associated with the systematic uncertainties are modeled through log-normal distributions for uncertainties in the normalization. Uncertainties in the shape of the distributions are modeled through "template morphing" techniques [55]. The limits are obtained from the entire m_{T} spectrum for $m_{\mathrm{T}} > 320$ GeV, as displayed in Fig. 3. This procedure is performed for different values of parameters of each signal, to obtain limits in terms on these parameters, such as the W′ boson mass.

Table 1: Expected yields for the signal and background events compared to the measured event yields in data, for three regions of m_T. Also shown are the total systematic uncertainties in the estimate of the event numbers.

Range of m_T	$m_T < 0.5$ TeV	$0.5 < m_T < 1$ TeV	$m_T > 1$ TeV
W + jets	786 ± 110	355 ± 68	21.8 ± 6.2
$Z \to \nu\nu$ + jets	238 ± 120	68 ± 35	0.9 ± 0.5
Multijet	68 ± 35	18 ± 10	<0.1
$t\bar{t}$	68 ± 15	14.5 ± 4.5	<0.1
$Z \to \ell\ell$ + jets	35.8 ± 8.7	10.4 ± 5.1	<0.1
Diboson (WW, WZ, Z Z)	24.9 ± 6.4	9.6 ± 3.5	0.7 ± 0.1
Single top quark	21.5 ± 6.5	7.0 ± 2.9	<0.1
Total background	1243 ± 160	485 ± 77	23.4 ± 6.2
SSM W′ $M = 600$ GeV	28229 ± 4388	14012 ± 2798	45.6 ± 7.7
SSM W′ $M = 1$ TeV	3767 ± 590	10079 ± 1581	355 ± 98
SSM W′ $M = 4$ TeV	0.7 ± 0.1	3.0 ± 1.8	11.4 ± 3.9
Data	1203	452	15

To determine a model-independent upper limit on the product of the cross section and branching fraction, all events above a threshold m_T^{min} are summed. From the number of background events, signal events, and observed data events, the cross section limit can be calculated. The resulting limit can be reinterpreted in the framework of other models with a τ_h and p_T^{miss} in the final state.

8.2 The sequential standard model W′

The parameter of interest is the product of the signal cross section and the branching fraction, $\sigma\mathcal{B}(W' \to \tau\nu)$. The branching fraction includes all τ lepton decay modes, to allow a direct comparison with the W′ searches in the electron and muon channels [9].

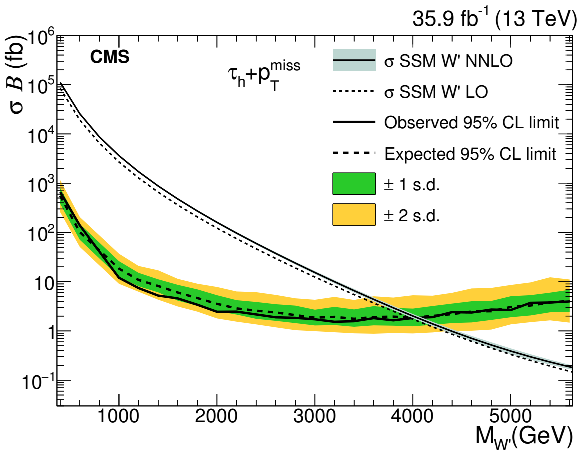

Figure 5: Expected (black dashed line) and observed (black solid line) 95% CL upper limits on the cross section for the production of SSM W′ boson. The shaded bands around the expected limit represent the one and two standard deviation (s.d.) uncertainty intervals. The NNLO theoretical cross section with the corresponding PDF uncertainty band is also shown.

The upper limit on $\sigma\mathcal{B}(W' \to \tau\nu)$ as a function of the SSM W′ boson mass is shown in Fig. 5. The observed limit is consistent with the expected limit. The SSM W′ boson is excluded for masses $0.4 < M_{W'} < 4.0$ TeV at 95% CL where the lower limit is mainly determined by the trigger threshold and the upper one by the available data. This result in the tau channel may be compared with the lower mass limit of 5.2 TeV for an SSM W′ boson, obtained from the combination of electron and muon channels [9, 56].

8.3 Limits on the coupling strength

The upper limits on the cross section depend not only on the mass of a potential excess, but also on the width. Because of the relation between the coupling of a particle and its width, a limit can also be set on the coupling strength. In order to compute the limit for couplings $g_{W'}/g_W \neq 1$, reweighted samples are used that take into account the appropriate signal width and the differences in reconstructed m_T shapes. For $g_{W'}/g_W = 1$ the theoretical LO cross sections apply. For a given mass, the cross section limit as a function of the coupling strength $g_{W'}/g_W$ is determined.

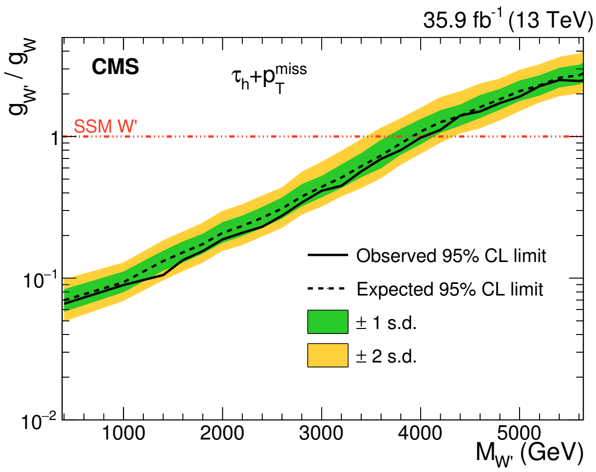

Figure 6: Expected (black dashed line) and observed (black solid line) 95% CL upper limits on the ratio of couplings as a function of the W′ boson mass. The values above the observed limit contour are excluded. The shaded bands around the expected limit represent the one and two standard deviation (s.d.) uncertainty intervals.

For each simulated W′ boson mass, the excluded cross section is determined from the intersection of the theoretical cross section curve with the observed cross section limit. The resulting intersection points provide the input for the exclusion limit in a two-dimensional plane made of $g_{W'}/g_W$ and $M_{W'}$, as depicted in Fig. 6. The phase space above the observed limit contour is excluded. For low masses, $g_{W'}/g_W$ values down to 7×10^{-2} are excluded.

8.4 The nonuniversal gauge interaction model limits

In the NUGIM G(221) framework, the ratio of the couplings $g_{W'}/g_W$ is related to the parameter $\cot\theta_E$ through Eq. 1. Thus $\cot\theta_E$ can be extracted for each value of $g_{W'}/g_W$. Based on the limits on coupling strengths presented in Fig. 6, the two-dimensional limit on $\cot\theta_E$ is shown as a function of the W′ boson mass. Fig. 7 (left) shows the width of the W′ boson as a function of $\cot\theta_E$ and $M_{W'}$. For $\cot\theta_E > 6.5$, the width becomes so large that the model is no longer valid. The limit, shown in Fig. 7 (right), focuses on the parameter space $\cot\theta_E \geq 1$ where the τ_h channel sets the most stringent bounds, as illustrated in Fig. 2. For lower values of $\cot\theta_E$, other channels are more sensitive. Depending on the value of $\cot\theta_E$, the mass of the W′ boson can be excluded at 95% CL up to 3.9 TeV in the NUGIM G(221) framework.

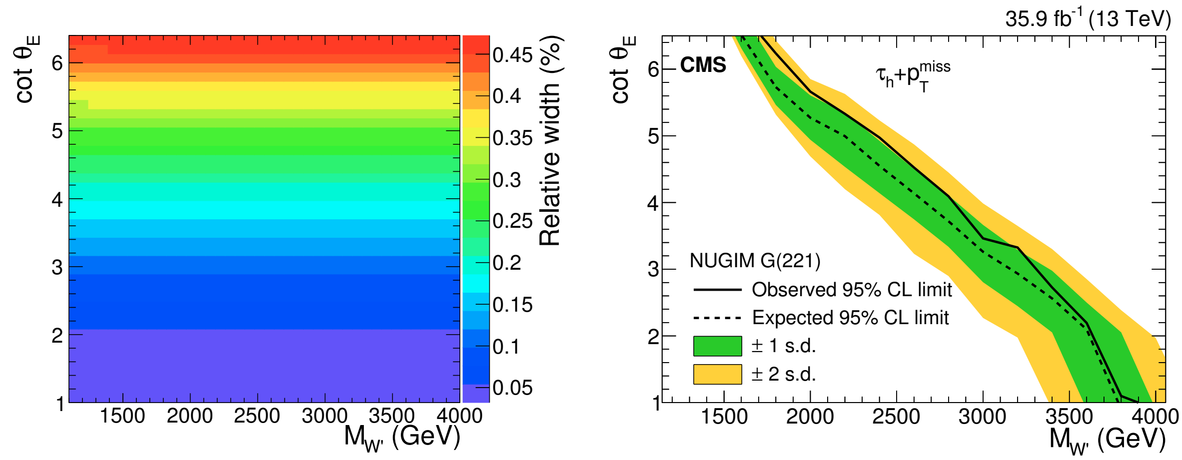

Figure 7: Left: The width of the W' boson as a function of $M_{\mathrm{W}'}$ and mixing angle $\cot\theta_{\mathrm{E}}$ in the NUGIM G(221) framework. Right: Expected (black dashed line) and observed (black solid line) 95% CL upper limits on the mixing angle $\cot\theta_{\mathrm{E}}$ as a function of the W' boson mass. The region left of the solid line is excluded. The shaded bands represent the one and two standard deviation (s.d.) uncertainty bands.

8.5 The model-independent cross section limit

The shape analysis assumes a certain signal shape in m_{T}. However, alternative new physics processes yielding a $\tau_{\mathrm{h}} + p_{\mathrm{T}}^{\mathrm{miss}}$ final state could cause an excess of a different shape. A model-independent cross section limit is determined using a single bin ranging from a lower threshold on m_{T} to infinity. No assumptions on the shape of the signal m_{T} distribution have to be made other than that of a flat product of acceptance times efficiency, $A\epsilon$, as a function of W' mass. In order to determine the limit for a specific model from the model-independent limit shown here, only the model-dependent part of the efficiency needs to be applied. The experimental efficiencies for the signal are already taken into account, including the effect of the kinematic selection of events containing τ_{h} and $p_{\mathrm{T}}^{\mathrm{miss}}$ (the selections on $p_{\mathrm{T}}/p_{\mathrm{T}}^{\mathrm{miss}}$ and $\Delta\phi$), the geometrical acceptance (selection on η), and the trigger threshold.

A factor $f_{m_{\mathrm{T}}}$ that reflects the effect of the threshold $m_{\mathrm{T}}^{\mathrm{min}}$ on the signal is determined by counting the events with $m_{\mathrm{T}} > m_{\mathrm{T}}^{\mathrm{min}}$ and dividing the result by the number of generated events. The reconstruction efficiency is nearly constant over the entire m_{T} range probed here, therefore $f_{m_{\mathrm{T}}}$ can be evaluated at generator level. A limit on the product of the cross section and branching fraction $(\sigma\mathcal{B}A\epsilon)_{\mathrm{excl}}$ can be obtained by dividing the excluded cross section of the model-independent limit $(\sigma\mathcal{B}A\epsilon)_{\mathrm{MI}}$ given in Fig. 8 by the calculated fraction $f_{m_{\mathrm{T}}}(m_{\mathrm{T}}^{\mathrm{min}})$:

$$(\sigma\mathcal{B}A\epsilon)_{\mathrm{excl}} = \frac{(\sigma\mathcal{B}A\epsilon)_{\mathrm{MI}}(m_{\mathrm{T}}^{\mathrm{min}})}{f_{m_{\mathrm{T}}}(m_{\mathrm{T}}^{\mathrm{min}})} \tag{3}$$

Here, $\mathcal{B}$ is the branching fraction of the new particle decaying to $\tau + \nu$. Models with a theoretical cross section $(\sigma\mathcal{B})_{\mathrm{theo}}$ larger than $(\sigma\mathcal{B})_{\mathrm{excl}}$ can be excluded. The procedure described here can be applied to all models involving the two-body decay of a massive state, which exhibit back-to-back kinematics similar to those of a generic W'. If the kinematic properties are different, the fraction of events $f_{m_{\mathrm{T}}}(m_{\mathrm{T}}^{\mathrm{min}})$ must be determined for the particular model considered.

The resulting cross section limit as a function of $m_{\mathrm{T}}^{\mathrm{min}}$ is shown in Fig. 8. The highest m_{T} event in data was found at 1.65 TeV, after which the limit becomes flat. The results depend strongly on the threshold $m_{\mathrm{T}}^{\mathrm{min}}$. Values of the product $\sigma\mathcal{B}A\epsilon$ between 50 fb ($m_{\mathrm{T}}^{\mathrm{min}} > 400\,\mathrm{GeV}$) and 0.4 fb

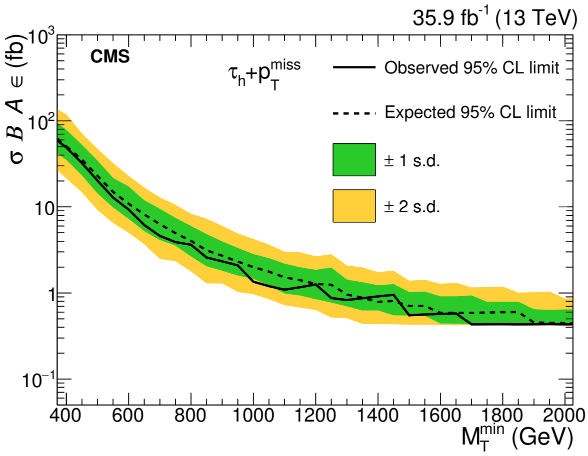

Figure 8: Expected (black dashed line) and observed (black solid line) 95% CL model-independent upper limits on the product of cross section, branching fraction, and acceptance for a resonance decaying into the $\tau\nu$ channel. The shaded bands represent the one and two standard deviation (s.d.) uncertainty bands.

($m_T^{min} > 2$ TeV) are excluded for the m_T^{min} thresholds given in brackets.

9 Summary

A search for new physics in final states with a hadronically decaying τ lepton and missing transverse momentum has been performed by the CMS experiment, using proton-proton collision data at the center-of-mass energy $\sqrt{s} = 13$ TeV with an integrated luminosity of 35.9 fb^{-1}. No significant excess compared to the standard model expectation is observed in the transverse mass of the tau and missing transverse momentum. A sequential standard model W′ boson is excluded in the mass range $0.4 < M_{W'} < 4.0$ TeV at 95% confidence level. Couplings that are weaker than assumed in the sequential standard model can be excluded down to values of 7×10^{-2} for $M_{W'} = 1$ TeV. Within the nonuniversal gauge interaction $SU(2) \times SU(2) \times U(1)$ model, the lower limit on the W′ boson mass depends on the coupling constant and varies from 1.7 to 3.9 TeV at 95% confidence level. For $\cot\theta_E > 1$, these results obtained in the tau channel provide the most stringent constraints on this model to date. In addition, a model-independent limit is provided allowing the results to be interpreted in other models giving the same final state with similar kinematic distributions.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF

(Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science - EOS" - be.h project n. 30820817; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Momentum") Programme and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850 and 125105 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

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