



# Search for $W'$ decaying to tau lepton and neutrino in proton–proton collisions at $\sqrt{s} = 8$ TeV



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## ABSTRACT

The first search for a heavy charged vector boson in the final state with a tau lepton and a neutrino is reported, using  $19.7 \text{ fb}^{-1}$  of LHC data at  $\sqrt{s} = 8$  TeV. A signal would appear as an excess of events with high transverse mass, where the standard model background is low. No excess is observed. Limits are set on a model in which the  $W'$  decays preferentially to fermions of the third generation. These results substantially extend previous constraints on this model. Masses below 2.0 to 2.7 TeV are excluded, depending on the model parameters. In addition, the existence of a  $W'$  boson with universal fermion couplings is excluded at 95% confidence level, for  $W'$  masses below 2.7 TeV. For further reinterpretation a model-independent limit on potential signals for various transverse mass thresholds is also presented.

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## 1. Introduction

New heavy gauge bosons are predicted by various extensions of the standard model (SM). Charged heavy gauge bosons are generally referred to as  $W'$  [1]. Non-universal gauge interaction models (NUGIM) [2–5] predict a larger  $W'$ -boson branching fraction to the third generation of fermions. Searches for a  $W'$  boson decaying to a tau lepton and neutrino have never been performed before, while the electron and muon channels have been studied extensively at the Tevatron [6,7] and by the ATLAS and CMS experiments at the LHC [8,9]. This Letter describes a search for a  $W'$  boson decaying to a tau lepton and a neutrino with the CMS detector [10] at the CERN LHC, using proton–proton collisions collected in 2012 at a center-of-mass energy of 8 TeV. The data set corresponds to an integrated luminosity of  $19.7 \pm 0.5 \text{ fb}^{-1}$ . The results are interpreted in the context of the sequential standard model (SSM)  $W'$  boson [1] as well as an extended gauge group NUGIM [2,11,12]. 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. Events of interest are those in which the only detectable products of the  $W'$  decay form a single hadronically decaying tau ( $\tau_h$ ). The hadronic decays of the tau lepton are experimentally distinctive because they result in low charged hadron multiplicity, unlike QCD jets, which have high hadron multiplicity, or other leptonic  $W'$  decays, which have none. In contrast, the decays  $W' \rightarrow \tau \nu_\tau \rightarrow e \nu_e \nu_\tau \nu_\tau$  and  $W' \rightarrow \tau \nu_\tau \rightarrow \mu \nu_\mu \nu_\tau \nu_\tau$  can-

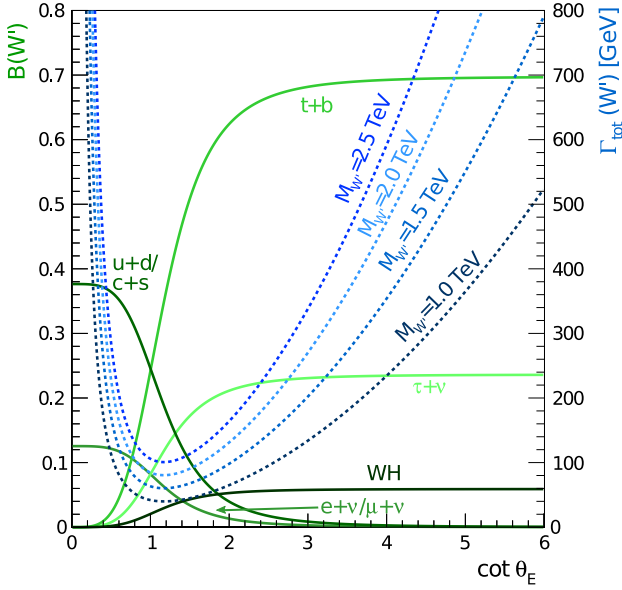
not be distinguished from  $W' \rightarrow e \nu_e$  and  $W' \rightarrow \mu \nu_\mu$ , thus they suffer from low significance and are not selected in this analysis but rather in the corresponding leptonic ( $e, \mu$ )  $W'$  searches.

## 2. Physics models

In the SSM, the  $W'$  boson is a heavy analogue of the  $W$  boson. It is a narrow resonance with fermionic decay modes and branching fractions similar to those of the SM  $W$  boson, with the addition of the decay  $W' \rightarrow tb$ , 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  $W' \rightarrow \tau \nu$  is 8.5%. Under these assumptions, the total width of a 1 TeV  $W'$  boson is about 33 GeV. Decays of the  $W'$  boson into  $WZ$  bosons depend on the specific model assumptions and are usually considered to be suppressed in the SSM, as assumed by the current search and by previous searches in other final states [9,13]. If the  $W'$  interacts with left-handed particles and right-handed anti-particles ( $V - A$  coupling), interference with the SM  $W$  boson is expected [14–16].

Models with non-universal couplings predict an enhanced branching fraction to the third generation of fermions and explain the large mass of the top quark. In the other model studied in this analysis, NUGIM [2,11,12], 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 couple only to the light fermions of the first two generations and to the heavy fermions of the third generation, respectively. These two groups mix such that an SM-like  $SU(2)_W$  and an extended group  $SU(2)_E$  exist. The second  $SU(2)_E$  extended

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**Fig. 1.** Branching fractions (left-hand scale and solid lines) and total width (right-hand scale and dotted lines) for  $W'$  decays in the NUGIM, as calculated in Refs. [2, 11,12]. For  $\cot\theta_E = 1$  the values are the same as those in the SSM, rescaled to accommodate the WH decay channel.

gauge group gives rise to additional gauge bosons such as a  $W'$ . The mixing of the two gauge groups is described by a mixing angle of the extended group  $\theta_E$ , which modifies the coupling to the heavy bosons. Hence the mixing changes the production cross section and, as illustrated in Fig. 1, the branching fractions of the  $W'$ . For  $\cot\theta_E \gtrsim 3$  the  $W'$  boson decays to fermions of the third generation only, whereas at  $\cot\theta_E = 1$  the branching fractions are identical to those of the SSM, and the  $W'$  couples democratically to all fermions. For  $\cot\theta_E < 1$  the decays into light fermions are dominant. In the NUGIM, the decay into WZ bosons is negligible by construction. In either the SSM or the NUGIM, the presence of a  $W'$ -boson signal over the W-boson background could be observed in the distribution of the transverse mass ( $M_T$ ) of the  $\tau_h$  and the missing transverse energy ( $E_T^{\text{miss}}$ ):

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

where  $p_T^\tau$  denotes the  $p_T$  of the  $\tau_h$  and  $E_T^{\text{miss}} = |\vec{p}_T^{\text{miss}}|$ , where  $\vec{p}_T^{\text{miss}}$  is defined as  $-\sum \vec{p}_T$  of all reconstructed particles. The angle in the transverse plane between  $\vec{p}_T^{\text{miss}}$  and the direction of  $\tau_h$  is denoted  $\Delta\phi(\tau, \vec{p}_T^{\text{miss}})$ .

### 3. Generation of background and signal samples

The major SM backgrounds are dominated by W and Z+jets production and are generated using MADGRAPH 5.1 [17] (for on-shell W and Z+jets backgrounds), PYTHIA 6.426 [18] (for off-shell W, WW, WZ, and ZZ backgrounds) and POWHEG 1.0 [19–23] (for  $t\bar{t}$  and single t+jets). The tau decay is simulated by TAUOLA [24] for all samples. For the hadronization of the MADGRAPH background, PYTHIA is used. The response of these events in the CMS detector is simulated using GEANT4 [25]. The backgrounds are produced at leading-order (LO), but reweighted to higher order cross sections. For the main W+jets background, a differential cross section as a function of the mass of the W-boson decay products is reweighted, incorporating next-to-next-to-leading-order (NNLO) QCD and next-to-leading-order (NLO) electroweak corrections. The effect with respect to the LO calculation corresponds to a K-factor of 1.3 at a mass of 0.3 TeV and drops for higher masses to 1.1

for a mass of 1 TeV. The calculation uses Monte Carlo generators MCSANC 1.01 [26] and FEWZ 3.1 [27], following the recommended combination from Ref. [28]. For the Z+jets background, the inclusive NNLO QCD cross section is calculated using FEWZ. For  $t\bar{t}$  events, the inclusive NNLO calculation from [29] is used. For the diboson (VV) backgrounds, inclusive NLO QCD cross sections are calculated using MCFM 6.6 [30]. The background contribution from multijet events is estimated from control samples in data. The signal events for the SSM  $W'$  are generated with PYTHIA with NNLO cross sections from FEWZ. The NUGIM signals are generated with MADGRAPH 4.5.1 [17] and hadronized with PYTHIA. The parton distribution functions (PDFs) used are CTEQ6L1 [31] for leading order simulation and CTEQ10 [32] for (N)NLO simulation. The electroweak NLO calculation NNPDF 2.3 at NNLO QCD with and without QED contributions [33] are used.

### 4. 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. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A particle-flow (PF) event algorithm [34] is used to reconstruct the events, identify the tau candidates and determine the missing  $E_T$ . The algorithm reconstructs and identifies single particles with an optimized combination of all subdetector information. The events are triggered by the CMS trigger system, which is split into two levels, a first level (L1) composed of custom hardware processors, and a high-level trigger (HLT) processor farm. For this analysis a “jet plus  $E_T^{\text{miss}}$ ” trigger is used, with thresholds of  $p_T > 80$  GeV for the jet and  $E_T^{\text{miss}} > 105$  GeV, where the latter is seeded at L1 in the calorimeter with  $E_T^{\text{miss}}$  above 40 GeV. Both objects are reconstructed at the HLT level using the PF event reconstruction. 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. [10].

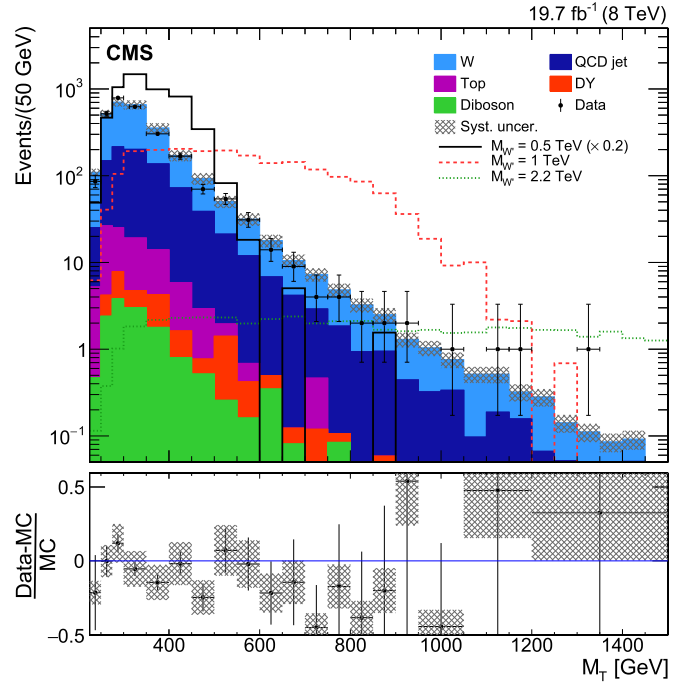
### 5. Reconstruction and identification of physics objects

Tau reconstruction in CMS [35] is applied to jets clustered from PF objects, using the anti- $k_T$  algorithm with a parameter  $R = 0.5$ . Tau candidates must be distinguished from quark or gluon jets (QCD jets in the following). The hadronic tau decays,  $\tau_h$ , are reconstructed using the “hadron-plus-strips” (HPS) algorithm, which is based on decay modes proceeding via specific intermediate resonances, with a combined branching fraction of 65%. They include modes with either one or three charged hadrons, and up to two neutral pions. Neutral pions are reconstructed via their decay into pairs of photons detected in the ECAL. The pattern of energy deposition in the ECAL typically occurs in “strips”, elongated in the  $\phi$  direction as a result of interactions in the tracker material and the effect of the axial magnetic field. The  $\tau_h$  candidate is reconstructed from strips and charged hadrons, which are combined using the mass ranges expected from the intermediate resonances. A more detailed discussion of the HPS algorithm can be found in [35]. The reconstruction of hadronic tau decays has been optimized for tau leptons with large  $p_T$  where different tracks potentially merge. This occurs because either the track reconstruction seed cannot be resolved or the tracks share so many hits that one track cannot be reconstructed. This leads to reconstructed decay modes with only

two charged hadrons (instead of three) being accepted to accommodate the boosted topology. The energy measurement of these high- $p_T$  objects is dominated by the calorimeter and therefore has a good  $p_T$  resolution. The allowed mass range for the intermediate state reconstruction is broadened for high- $p_T$  tau leptons, to compensate for the mass resolution. With these adaptations the tau reconstruction efficiency is constant at  $60\% \pm 6\%$  for  $p_T > 80$  GeV, as has been checked in simulations up to  $p_T = 3$  TeV. Hadronic tau decays identified by the HPS algorithm are required to be within the tracking acceptance,  $|\eta| < 2.3$ , and the tau  $p_T$  is required to be larger than 50 GeV to reduce the contamination from QCD jets. Additionally the  $p_T$  of the leading charged hadron is required to be larger than 20 GeV. Subsequently,  $\tau_h$  is distinguished from other objects that could mimic a tau candidate, such as QCD jets, electrons, or muons. The discriminator against QCD jets is the most important, since the rate of QCD jets at the LHC is several orders of magnitude larger than the tau production rate. Discrimination is based on isolation criteria: no additional PF charged hadrons or photons with  $|\sum \vec{p}_T|$  above 2 GeV are allowed in an isolation cone of  $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$  (where  $\phi$  is the azimuthal angle in radians and  $\eta$  is the pseudorapidity) around the  $\tau_h$  candidate direction. Particle-flow objects are corrected for additional collisions in the same bunch crossing (pileup). Charged hadrons are identified as pileup objects by vertex association. Neutral particle candidates are corrected by using an average  $p_T$  subtraction from the charged hadrons identified as pileup in a  $\Delta R = 0.6$  cone. Details can be found in Ref. [35]. Discrimination against electrons is obtained using a multivariate technique, based on various tau, photon, track and electron properties. The muon discriminator searches for hits in the muon system associated with the track of the  $\tau_h$  candidate. Both discriminators suppress light leptons by three orders of magnitude, without a significant reduction of the tau efficiency. Events of interest for this analysis are required not to contain identified electrons or muons. Electrons are required to satisfy shape and isolation criteria as well as  $p_T > 20$  GeV, and  $|\eta| < 1.44$  or  $1.56 < |\eta| < 2.50$ . Muons are required to be isolated and to have  $p_T > 20$  GeV and  $|\eta| < 2.4$ .

## 6. Analysis strategy

The strategy of this analysis is to select a heavy boson decaying almost at rest into  $\tau_h$  and  $E_T^{\text{miss}}$ . In the tau channel, the impact of the interference between  $W'$  and  $W$  bosons is expected to be substantially lower than that previously found in the electron and muon channels [9]. This occurs because the signal shape of a  $W'$  boson with hadronically decaying tau leptons does not show a Jacobian peak structure, because of the presence of two neutrinos in the final state. The interference effect has therefore not been considered in this analysis. For the “jet+ $E_T^{\text{miss}}$ ” trigger, analysis thresholds of  $p_T > 100$  GeV for the leading jet and  $E_T^{\text{miss}} > 140$  GeV are applied to account for differences of trigger and reconstructed energy definitions. These analysis thresholds on the tau  $p_T$  and  $E_T^{\text{miss}}$ , along with the kinematic selection on the ratio of  $p_T^\tau/E_T^{\text{miss}}$ , yield an implicit lower threshold on the transverse mass. The event is required to contain one isolated tau lepton. Two kinematic criteria are applied to select signal events: the ratio of the  $\tau_h$   $p_T$  to the  $E_T^{\text{miss}}$  is required to satisfy  $0.7 < p_T^\tau/E_T^{\text{miss}} < 1.5$  and the angle  $\Delta\phi(\tau, \vec{p}_T^{\text{miss}})$  has to be greater than 2.4 radians. This event selection mainly reduces the background in the low- $M_T$  region, which has the largest background, while the signal efficiency at high  $W'$  masses is only reduced by about 5%. The efficiency and acceptance for a  $W' \rightarrow \tau\nu$  event depend on the mass. For  $M_{W'} = 2.2$  TeV, 21% of the events pass all identification and selection criteria. This reduces to 17% for  $M_{W'} = 1$  TeV, 7% for  $M_{W'} = 0.5$  TeV, and, at



**Fig. 2.** The  $M_T$  distribution after the final selection. Data points with error bars show LHC data. The horizontal error bar on each point indicates the width of the bin, which is 25 GeV for the first three bins and 50 GeV for all other bins. The filled histogram shows the background estimate discussed in the text, and the hatched area the uncertainty in this estimate. The signal shapes for different SSM  $W'$  boson masses are shown as open histograms. The cross section for SSM  $M_{W'} = 500$  GeV is scaled by 0.2. In the ratio plot the bin-width is increased where needed to have at least one expected background event in each bin.

higher masses, to 16% at  $M_{W'} = 3$  TeV. The reduction for lower masses occurs because of the change in shape of the  $M_T$  distribution illustrated in Fig. 2, while for higher masses the off-shell production becomes dominant and shifts the events to lower  $M_T$ . From the simulation of hadronic tau events with large  $M_T$  values, above the kinematic turn-on, 42% are accepted once all selection and identification criteria are taken into account. This acceptance is independent of the  $W'$  mass. For the example case of  $W' \rightarrow \tau\nu$  with  $M_{W'} = 2.2$  TeV, the cross section calculated in the SSM is 13.5 fb. This yields 54.8 predicted signal events in the  $\tau_h + E_T^{\text{miss}}$  final state, with the 21% acceptance quoted above for this  $M_{W'}$  value. The variation of the predicted SSM cross section with  $W'$  mass can be seen in Fig. 3.

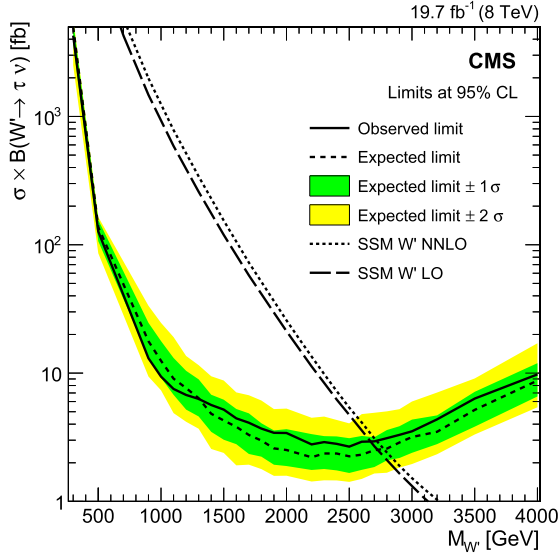
## 7. Background estimation

The transverse mass distribution with the observed data and expected background events and uncertainties is shown in Fig. 2 and Table 1. The dominant background, contributing almost two thirds of the total, comes from the off-shell tail of the SM  $W$  boson. This background is indistinguishable from the signal, and is estimated from simulation. The contribution from  $W \rightarrow e/\mu + \nu$  events, in which the electron or muon is not identified, is also taken from simulation. The background contribution from events with one QCD jet falsely identified as a  $\tau_h$  is suppressed by the  $p_T^\tau/E_T^{\text{miss}}$  requirement. Nonetheless it is the second largest background for this search and is estimated from data using reference regions, separated from the signal region using the uncorrelated quantities,  $p_T^\tau/E_T^{\text{miss}}$  and  $\tau_h$  isolation. The shape of the QCD jet background is estimated using data events with a jet identified as a  $\tau_h$ , fulfilling all kinematic criteria described earlier, apart from the isolation requirement. Its normalization is based on the ratio

**Table 1**

 The event yields for observed data and estimated backgrounds, and the product of acceptance and efficiency for the signal ( $W' \rightarrow \tau\nu$ ) for different threshold values  $M_T^{\text{min}}$ .

$M_T^{\text{min}}$ [GeV]	Data	VV	DY	Top	QCD jets	W	Sum of backgrounds	Efficiency for $M_W = 2.2$ TeV
200	1990	10	10	54	620	1380	$2080 \pm 34(\text{stat}) \pm 250(\text{syst})$	0.21
400	364	2.3	2.9	7.6	151	234	$398 \pm 5.5(\text{stat}) \pm 63(\text{syst})$	0.19
600	41	0.61	0.37	0.34	18.2	32.2	$51.7 \pm 1.3(\text{stat}) \pm 9(\text{syst})$	0.16
800	10	0.064	0.072	0	3.6	7.4	$11.1 \pm 0.49(\text{stat}) \pm 2.1(\text{syst})$	0.12
1000	4	0.0091	0.027	0	1.07	1.94	$3.05 \pm 0.19(\text{stat}) \pm 0.66(\text{syst})$	0.096
1200	1	0.0031	0.016	0	0.31	0.61	$0.94 \pm 0.095(\text{stat}) \pm 0.22(\text{syst})$	0.071
1400	0	0.0011	0.0076	0	0.130	0.180	$0.319 \pm 0.046(\text{stat}) \pm 0.081(\text{syst})$	0.047



**Fig. 3.** Limits on the product of cross section and branching fraction into  $\tau\nu$  for a SSM  $W'$  boson. The solid line shows the limit observed with  $19.7 \text{ fb}^{-1}$  of data while the dashed line corresponds to the expected limit. The shaded bands indicate the 68% and 95% confidence intervals of the expected limit. The dotted and the long-dashed lines show the cross section prediction in the SSM as a function of the  $W'$  boson mass, in NNLO and LO, respectively.

of the numbers of events with an isolated  $\tau_h$  ( $N_{\text{iso}}$ ) to those containing a non-isolated  $\tau_h$  ( $N_{\text{non-iso}}$ ), determined in a signal-free reference region with  $p_T^\tau/E_T^{\text{miss}} > 1.5$ . This ratio is evaluated as a function of the hadronic decay modes of the tau lepton. The mean ratio of isolated to non-isolated events is  $R = N_{\text{iso}}/N_{\text{non-iso}} = 0.0066 \pm 0.12\%(\text{stat}) \pm 0.16\%(\text{syst})$ . Here the contribution of non-QCD events is subtracted. It amounts to 24% for  $N_{\text{iso}}$  and 11% for  $N_{\text{non-iso}}$ . The systematic uncertainty is estimated by changing the  $p_T^\tau/E_T^{\text{miss}}$  threshold and the variable in which the ratio  $R$  is binned. The number of QCD jet events in the signal region is estimated, using this method, to be  $620 \pm 124$  after subtracting the contamination of 32% from electroweak background events. An additional systematic uncertainty of 20% is included, derived from the normalization uncertainty in the electroweak background. Other sources of background considered include top quark production, either in pairs or singly; Drell–Yan (DY) events; and tau leptons produced in diboson (WW, WZ, ZZ) events. A large fraction of these are suppressed by requiring the back-to-back decay topology. These backgrounds are shown in Fig. 2 as Top, DY, and Diboson, respectively. They contribute a total of 3% to the background.

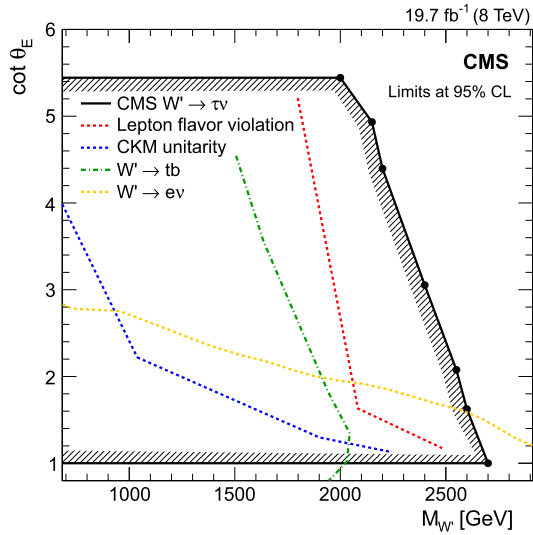
## 8. Systematic uncertainties

Most of the systematic uncertainties in this analysis affect the shape of the  $M_T$  distribution by changing the background and sig-

nal predictions. Others influence the overall normalization; these include the uncertainty of 2.6% [36] in the integrated luminosity. Simulated event samples are used to evaluate shape-dependent uncertainties arising from the measurement of individual particles and jets in the events. The kinematic variables of the individual objects are varied and the effect of the changes on the final  $M_T$  distribution is evaluated. In the following, the shape-dependent uncertainties are listed in decreasing order of their importance for the high- $M_T$  region. The main uncertainty in the background yield for  $M_T \geq 1$  TeV is due to the momentum measurement of the tau lepton [37], important for estimating the contribution from off-shell SM  $W$ -boson decays. Using  $Z \rightarrow \tau\tau$  events and tau-mass fits, the uncertainty in the momentum scale is estimated to be 3% of the tau  $p_T$ . This estimation is confirmed by comparing energy measurements from tau and jet reconstruction algorithms for high- $p_T$  taus. This results in a 15% scale uncertainty in the background event yield, primarily from the tail of off-shell SM  $W$  bosons, which is correlated with the uncertainty in the signal prediction. There is an 8% uncertainty in the event yield from the theoretical prediction of the background. One contribution to this theory uncertainty comes from the NNLO QCD and NLO electroweak calculations and is evaluated following the prescription described in Ref. [28]; there is an additional contribution from the PDFs, for which the prescriptions of Refs. [38,39] are used. The uncertainty in the event yield from the jet energy calibration is estimated to be 6%. The calibration uncertainty is dependent on the jet  $\eta$  and  $p_T$ , and is determined using dijet and  $Z \rightarrow \mu\mu + \text{jets}$  events [40]. The knowledge of the reconstruction efficiency for high- $p_T$  tau leptons is a source of uncertainty influencing the background and signal normalization. The efficiency is determined by studying  $Z \rightarrow \tau\tau$  and  $t\bar{t}$  processes [37]. The resulting uncertainty in the normalization is 6%. There is an uncertainty of 20% in the QCD jet contribution to the background, which is estimated from statistical uncertainties in the control regions and cross checks of the method, and which results in a 4–6% uncertainty in the overall background yield. Other sources of uncertainty are the jet energy resolution ( $\eta$  and  $p_T$  dependent) [40], pileup modeling (5% on the estimated number of additional interactions), and other factors affecting the  $E_T^{\text{miss}}$  determination, such as low-energy deposits not associated with a jet (10% uncertainty in the energy of deposits smaller than 10 GeV). The overall impact of these effects is a 6% background uncertainty. The impact of all these uncertainties on the signal acceptance has been evaluated using the simulated samples. The size and relative importance of the effects observed are similar to those for the background yield, and depend on the shape of the  $M_T$  distribution.

## 9. Results

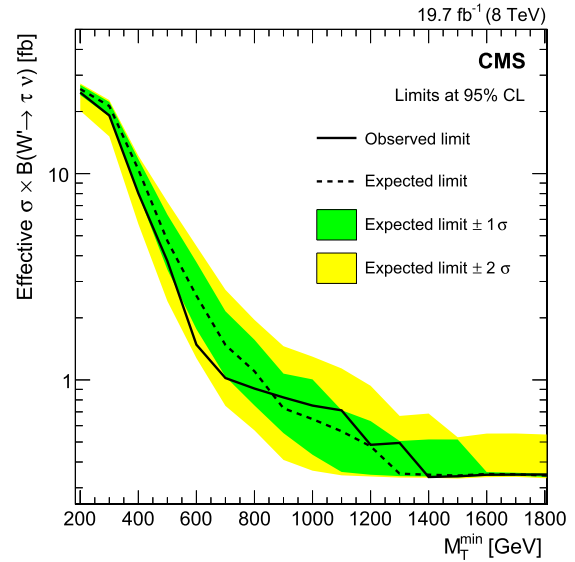
The final transverse mass distribution in Fig. 2 shows no significant deviations from the predicted background. A multibin approach is used to derive a limit on the  $W'$ -boson mass. A likelihood



**Fig. 4.** Limits on the NUGIM parameter space are shown from various analyses. The solid line refers to this analysis. The non-LHC limits (CKM and Lepton flavor violation) are calculated in Ref. [11]. The  $W'$  results are from Ref. [13] for the  $tb$  final state and Ref. [9] for  $ev$  as reinterpreted in Ref. [12]. The lines correspond to 95% CL limits.

function is evaluated separately using the numbers of events in each  $M_T$  bin. The likelihood functions from all bins are combined to extract the mass limit. For a more model-independent limit, a single-bin approach is used, counting all events above a threshold  $M_T^{\min}$  and comparing the number with the expected SM background. The parameter of interest is the product of the signal cross section and the branching fraction,  $\sigma \mathcal{B}(W' \rightarrow \tau \nu)$ . Limits are obtained at 95% confidence level (CL) using a Bayesian approach [41] with a uniform prior.

The limit on  $\sigma \mathcal{B}(W' \rightarrow \tau \nu)$  as a function of the SSM  $W'$ -boson mass is shown in Fig. 3. The observed and expected limits are in agreement. The SSM  $W'$  boson is excluded for masses  $0.3 < M_W < 2.7$  TeV at 95% CL in the tau channel. The lower mass limit is due to the trigger threshold and rising background. The  $W'$  mass limit obtained at 95% CL is 400 GeV lower for a signal cross section calculated to leading order. In the high mass region, off-shell production of  $W'$  bosons becomes dominant, shifting the signal  $M_T$  distribution to lower  $M_T$ . In comparison, analyses of the muon and electron channels have set limits of 3.0 and 3.2 TeV on the SSM  $W'$  mass, respectively [9]. In addition to the limit on the SSM  $W'$  boson, limits are set on the parameter space of the NUGIM. Only leading-order signal cross sections are available in the NUGIM. A separate cross section limit is derived for each value of the model parameter  $\cot \theta_E$ , since the signal efficiency depends on this parameter. The actual width of the  $W'$  resonance for a given mass, as shown in Fig. 1, is taken into account. From these limits, constraints on the mass of the  $W'$  boson as a function of the coupling parameter  $\cot \theta_E$  are derived in the same way as described previously for the SSM  $W'$  boson. The resulting constraints from these mass exclusion limits on the parameter space can be seen in Fig. 4. The  $W'$  mass limit is 2.0 TeV for  $\cot \theta_E = 5.5$ , rising to a  $W'$  boson mass of 2.7 TeV for  $\cot \theta_E = 1$ . This variation is due in part to the change in coupling strength to the tau lepton, which affects the decay, as shown in Fig. 1, and in part to the change in coupling to light quarks, which affects the production. For  $\cot \theta_E > 5.5$  the width of the  $W'$  becomes very broad, and large virtual corrections are needed. This search sets significantly better limits than the previous constraints from direct and indirect searches for large  $\cot \theta_E$  [9, 11, 13] reinterpreted in [12]. For  $\cot \theta_E < 1$ , the light families yield



**Fig. 5.** Model independent limits, on the effective cross section for a  $W'$ -like signal above a threshold value  $M_T^{\min}$ , for different  $M_T^{\min}$ . The solid line shows the limit observed with  $19.7 \text{ fb}^{-1}$  of data while the dashed line corresponds to the expected limit. The shaded bands indicate the 68% and 95% confidence intervals of the expected limit. The region above the curve is excluded.

a better sensitivity because of their higher efficiency and branching fraction as shown for the case of the electron channel in Fig. 4.

The multibin approach assumes a certain signal shape in  $M_T$ . However, new physics processes yielding a  $\tau + E_T^{\text{miss}}$  final state could cause an excess of a different shape. To be independent of models, a single-bin approach compares the number of observed events above a sliding  $M_T$  threshold, denoted  $M_T^{\min}$ , with the SM expectation for this  $M_T$  range. The resulting cross section limit as a function of  $M_T^{\min}$  is shown in Fig. 5. The reconstruction efficiency is estimated to be 42% for  $W'$  events satisfying the condition  $M_T > M_T^{\min}$ . It may be noted that the fraction of the signal that satisfies the  $M_T^{\min}$  requirement depends on the particular model, and is mass-dependent. The reconstruction efficiency has an uncertainty corresponding to that of a typical  $W'$ -like signal at different  $M_T^{\min}$  thresholds. This allows a reinterpretation in various models by evaluating the signal efficiency,  $\varepsilon_{\text{signal}}$ , for the  $M_T^{\min}$  threshold, defined as the number of events in the signal region with  $M_T > M_T^{\min}$  divided by the total number of generated events:  $\varepsilon_{\text{signal}} = N_{M_T > M_T^{\min}} / N_{\text{total}}$ .

## 10. Summary

In summary, the first search for an excess in the transverse mass distribution of the  $\tau + E_T^{\text{miss}}$  channel has been performed. The data sample was collected with the CMS detector in proton-proton collisions at  $\sqrt{s} = 8$  TeV, and corresponds to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ . No significant excess beyond the SM expectation is observed. An SSM  $W'$  boson is excluded in the mass range  $0.3 \text{ TeV} < M_W < 2.7 \text{ TeV}$  at 95% confidence level. Within the NUGIM the lower limit on the  $W'$ -boson mass depends on the coupling constant  $\cot \theta_E$  and varies from 2.0 to 2.7 TeV at 95% confidence level.

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