



Search for third-generation scalar leptoquarks and heavy right-handed neutrinos in final states with two tau leptons and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract

A search is performed for third-generation scalar leptoquarks and heavy right-handed neutrinos in events containing one electron or muon, one hadronically decaying τ lepton, and at least two jets, using a $\sqrt{s} = 13$ TeV pp collision data sample corresponding to an integrated luminosity of 12.9 fb^{-1} collected with the CMS detector at the LHC in 2016. The number of observed events is found to be in agreement with the standard model prediction. A limit is set at 95% confidence level on the product of the leptoquark pair production cross section and β^2 , where β is the branching fraction of leptoquark decay to a τ lepton and a bottom quark. Assuming $\beta = 1$, third-generation leptoquarks with masses below 850 GeV are excluded at 95% confidence level. An additional search based on the same event topology involves heavy right-handed neutrinos, N_R , and right-handed W bosons, W_R , arising in a left-right symmetric extension of the standard model. In this search, W_R bosons are assumed to decay to a tau lepton and N_R followed by the decay of the N_R to a tau lepton and an off-shell W_R boson. Assuming the mass of the right-handed neutrino to be half of the mass of the right-handed W boson, W_R boson masses below 2.9 TeV are excluded at 95% confidence level. These results improve on the limits from previous searches for third-generation leptoquarks and heavy right-handed neutrinos with τ leptons in the final state.

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1 Introduction

A number of extensions of the standard model (SM) have been proposed that predict an enhanced production rate for events containing pairs of quarks and pairs of third-generation leptons. One such theoretical proposal involves the existence of particles called leptoquarks (LQs), which carry color charge, fractional electric charge, and both lepton and baryon quantum numbers. The LQs arise in many models, including grand unified theories [1], compositeness models [2, 3], and superstring theories [4]. If LQs exist, they will decay into a lepton and a quark. Stringent limits on flavor changing neutral currents [5] indicate that the LQs would decay predominantly into a lepton and a quark of the same generation [3, 5–7]. The dominant production mechanism of LQ pairs at the CERN LHC is predicted to be gluon-gluon fusion, resulting in a large production cross section. The rate of pair production of scalar LQs is determined by the strong interaction and the only free parameter is the mass of the LQ. Thus, the production of LQ pairs is independent of the coupling of the LQ to SM fermions. However, the branching fraction for the decay of a LQ into a quark and a charged lepton, β , depends on the details of the model under consideration. In this analysis we focus on the decay of a pair of third-generation LQs resulting in two τ leptons and two jets originating from b quark fragmentation.

A similar final state is expected in theories that postulate that the masses of the familiar left-handed neutrinos arise not from the Higgs field, but from a mechanism that involves the existence of right-handed neutrinos. One of the appealing features of left-right (L-R) symmetric extensions [8] of the SM is that these models predict the existence of new heavy charged (W_R) and neutral (Z_R) gauge bosons that could be produced at LHC energies. Heavy neutrinos (N_e, N_μ, N_τ) naturally arise as the right-handed (RH) partners of the SM neutrinos in these L-R extensions through the see-saw mechanism [9].

In this paper, we search for these two processes by selecting final states containing two τ leptons and two jets originating from the hadronization of quarks. A search for pair production of third-generation scalar LQs is pursued by looking for events containing two τ leptons and two b quarks. We also search for the production of a W_R boson from quark-antiquark annihilation. A heavy right-handed neutrino is produced from the decay of the W_R boson following the decay chain $W_R \rightarrow \tau + N_\tau$, where $N_\tau \rightarrow \tau + W_R^* \rightarrow \tau + q\bar{q}$. In both searches, we focus on signatures with one of the τ leptons decaying into an electron or a muon, referred to as a leptonic decay τ_ℓ in the following, and the other τ lepton decaying hadronically, denoted by τ_h .

Previous searches for third-generation LQs have been carried out at pp, $p\bar{p}$, e^+e^- , and ep colliders and the most recent results are given in [10, 11] and references therein. The most stringent lower limit on the mass of scalar third-generation LQs to date, based on the final state with two τ leptons and two b jets and assuming $\beta = 1$, is 740 GeV at 95% confidence level (CL), from the CMS experiment [12, 13]. Previous searches for heavy neutrinos have been performed at LEP [14, 15], excluding heavy neutrino masses below approximately 100 GeV. Further searches at LHC have been performed in the dielectron and dimuon channels and have excluded W_R bosons with mass up to 3 TeV using data taken at 7 TeV [16] and at 8 TeV [17]. Using 2.1 fb^{-1} of data of 13 TeV pp collisions collected in 2015, the CMS experiment searched for heavy neutrinos and right-handed charged bosons using events in which both τ leptons decay hadronically. That analysis excluded W_R bosons with masses below 2.35 (1.63) TeV at 95% CL, assuming the N_τ mass is 0.8 (0.2) times the mass of W_R boson [13]. In the present search, we use a $\sqrt{s} = 13 \text{ TeV}$ pp collision data sample corresponding to an integrated luminosity of 12.9 fb^{-1} collected with the CMS detector in 2016.

2 The CMS detector and Monte Carlo event samples

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid. A 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. [18].

The first level of the CMS triggering system, composed of custom hardware processors, uses information from the calorimeters and the muon detectors to select the most interesting events in a fixed time interval of less than 4 μ s. The high-level trigger processor farm further decreases the event rate from around 100 kHz to less than 1 kHz.

Background and signal processes are modeled using the following simulated samples. The PYTHIA v8.205 generator [19] is used to model the signal and diboson (WW , WZ , and ZZ) processes. The LQ signal samples are generated with masses ranging from 250 to 1500 GeV in steps of 50 GeV in the LQ mass. The branching fraction of the LQ to a τ lepton and a bottom quark is assumed to be 100%. The signal samples are normalized to the next-to-next-to-leading order [20, 21]. The W_R signal samples are generated with masses ranging from 1000 to 4000 GeV in steps of 500 GeV W_R boson and the cross sections are computed in Ref. [22]. The MADGRAPH v5.1.5 generator [23] is used to model W +jets and Z +jets processes. Single top production and $t\bar{t}$ process are modelled with the POWHEG 2.0 [24–26] generator. The NNPDF 3.0 [27] Parton Distribution Functions (PDF) are used, and all simulated samples are interfaced with PYTHIA with the CUETP8M1 tune [28] to describe parton showering and hadronization. All the generated signal and background samples are processed with the simulation of the CMS detector based on GEANT4 [29]. Small differences between data and simulation in trigger, in particle identification and isolation efficiencies, and in the resolution of the p_T of jets and missing transverse momentum are corrected by applying scale factors to simulated events, as detailed below.

3 Event reconstruction and selection

The particle-flow (PF) algorithm [30, 31], which exploits information from all subdetectors, is used to identify individual particles, such as charged and neutral hadrons, muons, electrons, and photons. These reconstructed particles are used as input for reconstructing more complex objects such as τ_h candidates, jets, and variables like missing transverse momentum.

The reconstructed interaction vertex with the largest value of $\sum_i (p_T^i)^2$, where p_T^i is the transverse momentum of the i th track associated with the vertex, is selected as the primary vertex of the event. This vertex is used as the reference vertex for all the objects reconstructed using the PF algorithm.

Electrons are reconstructed by matching the energy deposits in the ECAL to tracks reconstructed in the silicon pixel and strip detectors. The electrons selected in this analysis are required to have transverse momenta $p_T > 50$ GeV and pseudorapidity $|\eta| < 2.1$ [32]. The identification and isolation of electrons are based on a multivariate technique [33] and selected electrons must satisfy tight electron identification and isolation criteria.

Muon reconstruction starts by matching tracks in the silicon tracker with tracks in the outer

muon spectrometer [34]. A global muon track is fitted to the hits from both tracks. Muons are required to have $p_T > 50$ GeV and $|\eta| < 2.1$. Quality selection criteria are applied to the muon tracks to distinguish muons originating from particle collisions with those muons coming from cosmic rays. In addition, muons are required to pass isolation criteria to separate prompt muons from those associated with a jet, usually from the semileptonic decays of heavy quarks.

The hadron-plus-strips algorithm [35, 36] is used to reconstruct τ_h candidates. It starts from a jet and searches for candidates produced by the main hadronic decay modes of a τ lepton: either directly to one charged hadron, or via intermediate $\rho(770)$ and $a_1(1280)$ mesons to one charged hadron plus one or two neutral pions, or three charged hadrons. The reconstructed τ_h is required to have $|\eta| < 2.3$ and $p_T > 50$ ($p_T > 60$) GeV in the LQ (heavy RH neutrino) search. Hadronic tau lepton decays are identified by a multivariate technique that uses as inputs the isolation of the τ_h and variables that are sensitive to its lifetime. A selection criterion is used that has an efficiency of approximately 65% for identifying hadronically decaying tau leptons and a probability of less than 1% for misidentifying jets as hadronic tau decays. Additional criteria are applied to remove electrons and muons reconstructed as τ_h candidates.

The identified electron or muon and the τ_h are required to originate from the same vertex and be spatially separated by $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.5$. To suppress background events such as diboson and Z+jets with bosons decay giving a final state with a pair of leptons, events containing additional electron or muon candidates with $p_T > 15$ GeV, and which pass loose identification and isolation criteria, are rejected.

Jets are reconstructed using the anti- k_T algorithm with a distance parameter of $R = 0.4$ [37, 38] using PF candidates. The jet energy is corrected for the average contribution from particles from other proton-proton collisions in the same or neighbouring bunch crossings (pileup) [39]. An additional correction is applied to better reflect the true total momentum of the particles in the jet [40]. Selected jets are required to be within $|\eta| < 2.4$ and have $p_T > 50$ GeV, and to be separated from the selected electron or muon and the τ_h by $\Delta R > 0.5$. Further identification requirements are applied to distinguish genuine jets from those coming from pileup [41].

The transverse momentum imbalance, (\vec{p}_T^{miss}), is calculated as the negative vectorial sum of transverse momenta of all PF candidates, and corrected by propagating the corrections applied to identified jets [42]. A correction is applied to account for the effect of additional pileup interactions. In addition, several filters are employed to veto events with large \vec{p}_T^{miss} caused by detector effects.

Candidate events were collected using a set of triggers requiring the presence of either an electron or a muon candidate with $p_T > 45$ GeV.

The search for LQs is based on a sample of events containing one light lepton, one τ_h candidate, and at least two jets. At least one of the two leading jets is identified as originating from b quark hadronization (b-tagged) using the combined secondary vertex algorithm [43]. The chosen b tagging working point corresponds to an identification efficiency of approximately 70% with about 1% misidentification rate from light quarks. The lepton and τ_h candidate are required to have opposite electric charge. There are two possible combinations of two tau candidates, with two jets, and the combination that minimises the difference in masses between the two resulting tau candidate-jet systems is chosen. Additionally, the invariant mass of the system formed by the visible particles of the τ_h candidate and a jet is required to be greater than 250 GeV.

The search for a W_R boson decaying into a heavy neutrino uses the same data sample as used by the LQ search. The \vec{p}_T^{miss} is required to be above 50 GeV and the invariant mass of the light

lepton and the τ_h is required to be greater than 150 GeV.

In the LQ analysis, the fraction of signal events passing all selection cuts ranges between 1 and 5% for masses between 300 and 1500 GeV, and in the W_R analysis the fraction varies between 2 and 7% for masses between 1 and 4 TeV.

The presence of a signal is investigated by analysing the distribution of S_T . This is defined as the scalar sum of the p_T of the electron or muon, the τ_h candidate, the two jets, and the missing transverse energy.

4 Background estimation

Several SM processes can mimic the signatures explored in this search. Production of $t\bar{t}$ pairs is the dominant background because of the presence of genuine leptons, \vec{p}_T^{miss} , and both light- and heavy-flavour jets. Additionally, the production of a W or Z boson in association with jets, production of a diboson or a single top quark, and Quantum ChromoDynamics (QCD) multijet processes can also contribute to the SM background contributions.

Simulated $t\bar{t}$ events are reweighted according to the top quark p_T distribution measured in data [44, 45]. The normalization and shape of the $t\bar{t}$ background is then verified by comparing to a data sample that consists of events containing an electron, a muon, and at least two jets and including all final selection requirements. The purity of $t\bar{t}$ events in this sample exceeds 95%. Signal contamination in this control region is found to be negligible and does not affect the comparison of data with simulation even in the tail of the S_T distribution. The normalization and shape of the $t\bar{t}$ simulated sample agree well with those observed in data. Thus, the simulation is used to predict the $t\bar{t}$ background in the signal region.

The W +jets background arises mainly from events with a genuine electron or muon originating from the leptonic decay of a W boson and an initial- or final-state radiation jet misidentified as a τ_h candidate. The normalization and shape of the W background are obtained from simulation and a correction factor is applied to the normalization to take into account differences between data and simulation. The W background correction factor is estimated in a data sample that consists of $W \rightarrow \mu\nu$ events with three or more jets. One of the jets is required to pass the τ_h identification criteria. To reduce the contamination from $t\bar{t}$ background, events containing jets that pass the b tagging criteria are rejected. The expected signal contamination in this sample is negligible. A binned maximum likelihood fit to the transverse mass distribution of the muon and \vec{p}_T^{miss} is then performed to derive the W background normalization correction factor. The transverse mass distribution is found to have the most discriminating power for separating the W background from the other backgrounds. As an input to the fit, the normalization and shape of all other contributions are estimated from simulation. The uncertainties in the cross sections of all backgrounds are included as nuisance parameters in the fit. The contamination from QCD multijet events is small and derived from simulation. The best fit value for the W normalization correction factor is found to be 1.0 ± 0.2 . A similar procedure is repeated for the $e\tau_h$ channel in a control region containing events with an electron and three or more jets. The W +jets normalization factor measured in $W \rightarrow e\nu$ events is found to be consistent with the normalization factor derived in $W \rightarrow \mu\nu$ events, albeit with a slightly larger uncertainty.

The contribution of the QCD multijet background to the signal region in both the $\mu\tau_h$ and $e\tau_h$ channels is estimated from data. Events in the multijet control region are selected by inverting the τ_h identification criteria: the τ_h candidate is required to pass looser, but to fail tighter, identification criteria. The events are weighted by the p_T -dependent probability for a jet satisfying

loose isolation criteria to pass the tight τ_h isolation criteria. This probability is measured as a function of jet p_T for $e\tau_h$ and $\mu\tau_h$ channels separately, in independent data samples that are composed of events in which the lepton fails the isolation criteria and has the same charge as τ_h candidate.

Other minor backgrounds, arising from single top quark, Z boson, and diboson production are estimated from simulation.

5 Systematic uncertainties

The results of the analysis are obtained from a binned fit to the S_T distributions in the $e\tau_h$ and $\mu\tau_h$ channels. Systematic uncertainties may affect the normalization and/or the shape of the S_T distribution of the signal and background processes.

The uncertainty in the integrated luminosity of the analysed dataset amounts to 6.2% [46]. Uncertainties in the muon and electron identification and trigger efficiency are determined using the “tag-and-probe” technique [47] and amount to 2% for identification and 5% for trigger efficiencies. The τ_h identification efficiency [35, 48] is measured in bins of τ_h candidate p_T in $Z \rightarrow \tau\tau$ and $W \rightarrow \tau\nu$ events and fitted by a linear function within the range 20 to 200 GeV. The uncertainty in the τ_h identification efficiency measurement is 6% for τ leptons from the decay of Z bosons. The extrapolation to higher transverse momenta is taken into account by adding an uncertainty that increases linearly with p_T and has a value of 20% for a p_T of 200 GeV. This uncertainty has a direct effect on the S_T distribution and hence is considered as a shape uncertainty. Changes in the acceptance due to the uncertainty in the b tagging efficiency and in the mistag rate are measured to be between 3 and 5%, depending on the process. The uncertainty in the normalization of the $t\bar{t}$ background due to the PDF and scale uncertainties amounts to 5% [49, 50]. A 10% uncertainty is attributed to the Z boson background estimate, while the uncertainty in both the diboson and single top background estimates amounts to 15% [51]. The uncertainty in the yield of QCD multijet and W +jet backgrounds amounts to 30%. The uncertainty in the signal acceptance due to the choice of the PDF set in the simulated sample is evaluated in accordance to the PDF4LHC recommendations [50, 52], by comparing the results obtained using the CTEQ6.6L, MSTW08, and NNPDF10 PDF sets [53–55] with those from the default PDF set (CTEQ6L1). This uncertainty amounts to 5% [13].

The energy scales (ES) of the τ_h candidate and the associated jet affect the shape of the S_T distribution and normalization of the signal and background processes. The effects of ES uncertainties on the analysis are estimated by varying the τ_h and jet energies within their respective uncertainties and recomputing S_T after the final selection. The uncertainty in the τ_h ES amounts to 3% [35]. The uncertainty in the jet ES affects the p_T spectrum of the jets and consequently \vec{p}_T^{miss} , and is applied to all backgrounds that are estimated with MC simulation [56]. The uncertainties in the electron, muon, and \vec{p}_T^{miss} ES have a negligible effect on the S_T distribution. The uncertainty in the top quark p_T reweighting correction is derived by changing the event weight between zero and twice the nominal reweighting correction value [44, 45]. All these three uncertainties are treated as correlated between the $e\tau_h$ and $\mu\tau_h$ channels.

Finally, the effects of statistical uncertainties associated with the background shapes or with the numbers of events in the data control regions are included in the analysis. The statistical uncertainties are uncorrelated across the bins in each background distribution [57].

Systematic and statistical uncertainties are represented by nuisance parameters in the fit. A log-normal probability distribution function is assumed for the nuisance parameters that affect the

event yields of the various background contributions. Systematic uncertainties affecting the S_T distributions are assumed to have a Gaussian probability distribution function. Among those uncertainties, the τ_h ES and high p_T τ_h extrapolation uncertainties are uncorrelated between the $e\tau_h$ and $\mu\tau_h$ channels, because of the different τ_h identification criteria used to reduce the electron and muon mis-identification rate in each channel. The jet ES is treated as correlated across the two channels.

6 Results

A binned maximum likelihood fit to the S_T distribution has been applied to the $e\tau_h$ and $\mu\tau_h$ channels simultaneously. The signal production rate is constrained to the same value in the two channels. The S_T distributions for the both channels are shown in Fig. 1 for both LQ and W_R analyses. Shape, normalization and uncertainty are shown for the values of nuisance parameters obtained from the fit. No excess is seen above the SM expectation within the statistical and systematic uncertainties in both searches.

Upper limits on the product of the cross section and branching fractions are set at 95% CL using a modified frequentist criterion CL_s [58, 59], based on the binned distribution of the S_T variable. Figure 2 (left) shows the observed and expected 95% CL upper limit on the product of cross section and branching fraction in the LQ analysis. The observed (expected) 95% CL mass limit for third-generation scalar LQ is determined to be 850 (900) GeV, respectively, assuming $\beta = 1$, namely a 100% branching fraction for the LQ to decay into a τ lepton and a bottom quark. Figure 2 (right) shows the 95% CL observed and expected exclusion limits on the LQ mass, as a function of β .

Figure 3 (left) shows the observed and expected upper limits at 95% CL on the product of cross section and branching fraction for the $W_R \rightarrow \tau N_\tau$ analysis. Assuming the mass of the neutrino to be half the mass of the W_R boson, the observed (expected) limit at 95% CL on the mass of heavy right-handed W_R bosons is determined to be 2.9 (3.0) TeV, respectively. Figure 3 (right) shows the observed and expected 95% CL upper limits on the production cross section as functions of M_{W_R} and M_{N_τ} . The blue curve in the left plot represent the theoretical production cross section of W_R boson times branching fraction of the W_R boson to a τ lepton and RH neutrino, assuming mass of RH neutrino to be half the mass of W_R boson.

7 Summary

Searches have been performed for third-generation scalar leptoquarks and for heavy right-handed neutrinos in events containing one electron or muon, one hadronically decaying τ lepton, and two or more jets, using pp collision data at $\sqrt{s} = 13$ TeV, recorded by the CMS detector at the LHC and corresponding to an integrated luminosity of 12.9 fb^{-1} . The data are found to be in good agreement with the standard model prediction in both analyses. A limit at 95% confidence level is set on the product of the leptoquark pair production cross section and β^2 , where β denotes the branching fraction for the decay of the leptoquark into a τ lepton and a bottom quark. Assuming $\beta = 1$, third-generation leptoquarks with masses below 850 GeV are excluded at 95% confidence level. In the heavy RH neutrino analysis, considering the decay $W_R \rightarrow \tau N_R$ and assuming the mass of the heavy neutrino to be half the mass of the W_R boson, we exclude W_R boson masses below 2.9 TeV at 95% confidence level. These are the best mass limits to date for third-generation leptoquarks and heavy right-handed neutrinos with τ leptons in the final state.

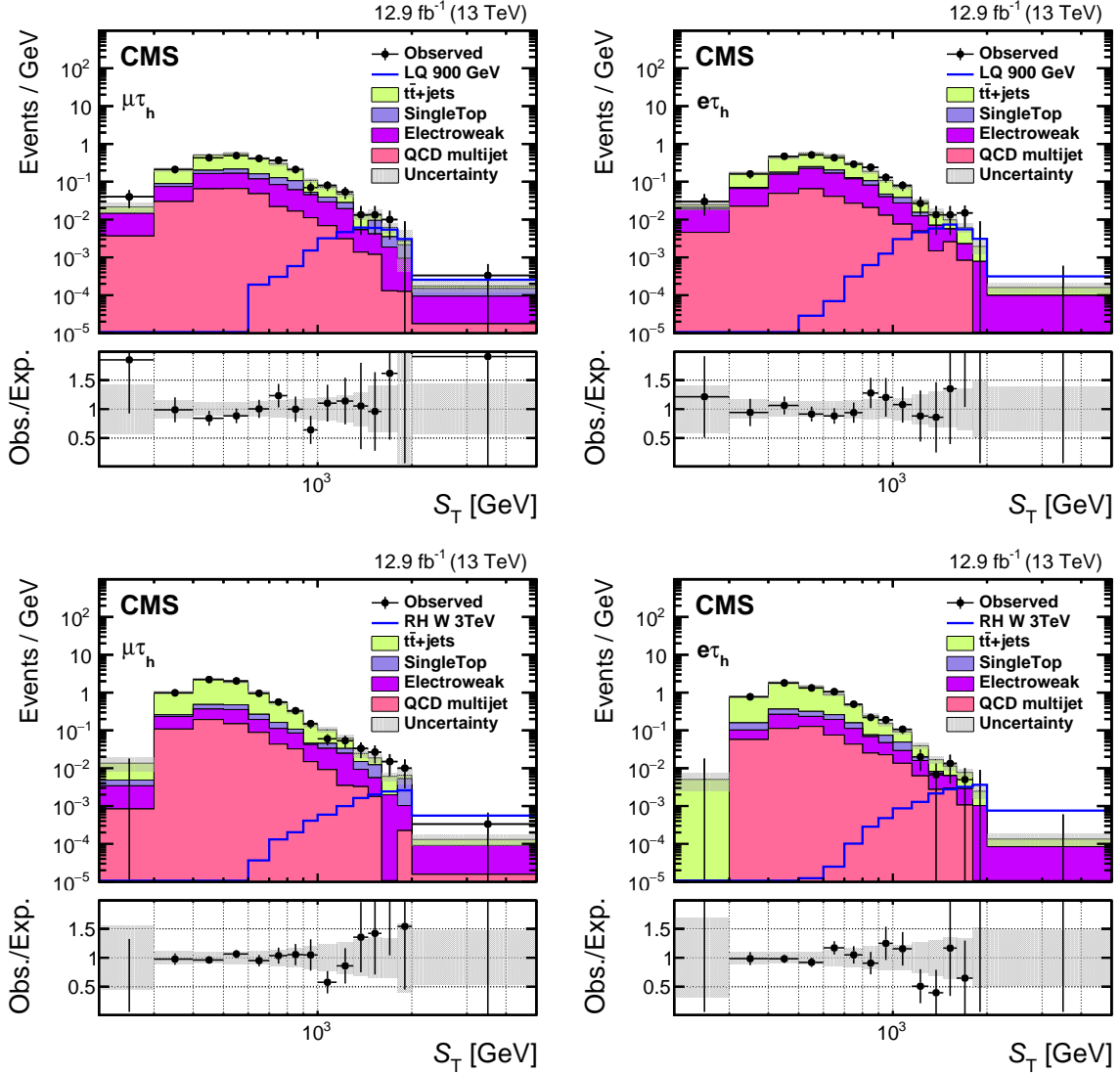


Figure 1: Measured S_T distribution in the $\mu\tau_h$ (left) and $e\tau_h$ (right) channels of the LQ (upper) and heavy RH neutrino (lower) analyses, compared to the expected SM background contribution. A hypothetical LQ signal of mass $M_{LQ} = 900$ GeV and a hypothetical heavy W_R signal of mass $M_{W_R} = 3$ TeV are overlaid to illustrate the sensitivity. The electroweak background represents the sum of W boson, Z boson, and diboson production. The last bin of each plot contains overflow events. A binned maximum likelihood fit is performed on the S_T distribution. The uncertainty bands represent the sum in quadrature of statistical and systematic uncertainties, obtained from the fit. The lower panels in all plots compare the observed and expected events in each bin of distribution.

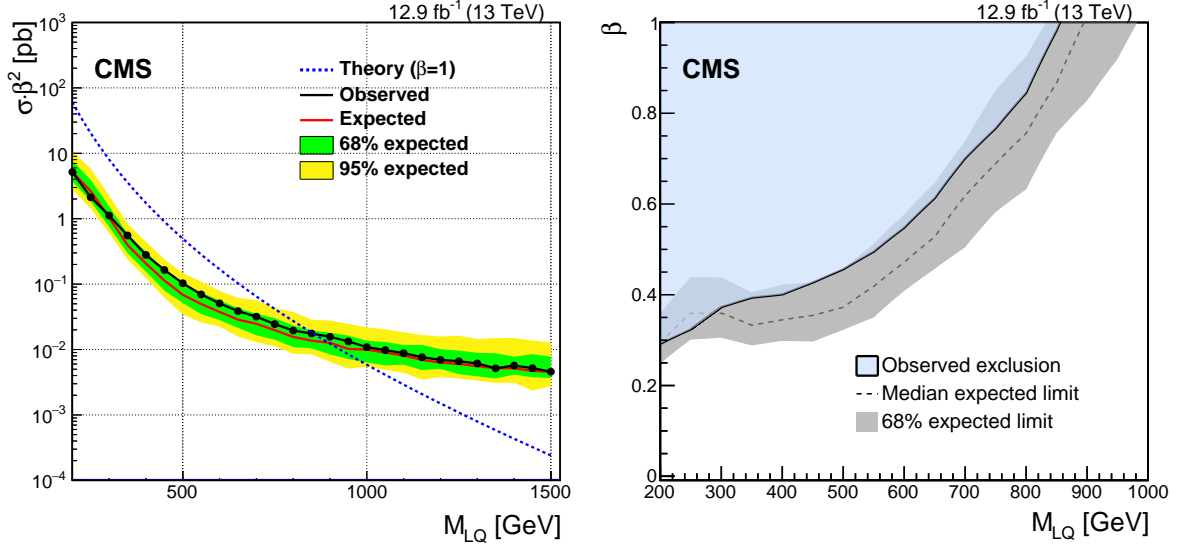


Figure 2: Observed and expected limits at 95% CL on the product of cross section and branching fraction squared, obtained from the combination of the $e\tau_h$ and $\mu\tau_h$ channels, in the LQ analysis (left) and 95% CL observed and expected exclusion limits on the LQ mass, as a function of β (right). In the left plot, the green and yellow bands represent the one and two standard deviation uncertainties in the expected limits. The dashed dark blue curve represents the theoretical LQ pair production cross section, assuming $\beta = 100\%$ [20, 21]. In the right plot, the grey band represents the one standard deviation uncertainty in the expected limit.

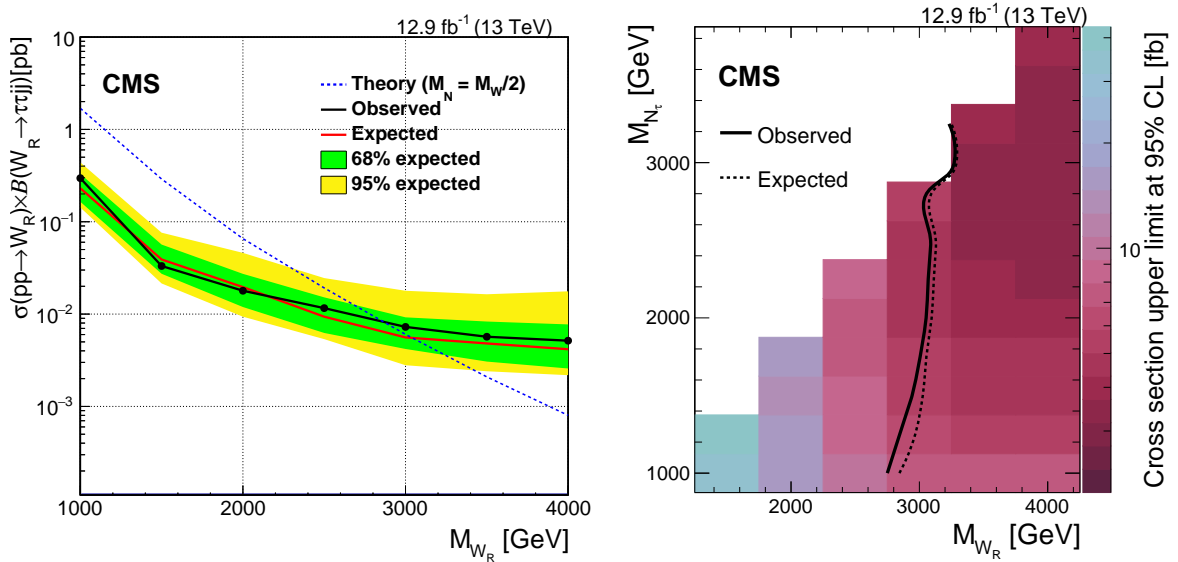


Figure 3: Observed and expected limits at 95% CL on the product of cross section and branching fraction, obtained from the combination of the $e\tau_h$ and $\mu\tau_h$ channels in the heavy right-handed neutrino analysis (left) and the observed and expected limits at 95% CL on the production cross section as a function of M_{W_R} and M_{N_R} (right). The green and yellow bands represent the one and two standard deviation uncertainties in the expected limits. The dashed dark blue curve represents the theoretical prediction for the product of the W_R boson production cross section and the branching fraction for decay to a τ lepton and RH neutrino, assuming the mass of the RH neutrino to be half the mass of the W_R boson [22].

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