Search for Scalar Leptoquarks Produced via τ-Lepton–Quark Scattering in pp Collisions at $\sqrt{s} = 13$ TeV

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The first search for scalar leptoquarks produced in τ-lepton–quark collisions is presented. It is based on a set of proton-proton collision data recorded with the CMS detector at the LHC at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 138 fb^{-1}. The reconstructed final state consists of a jet, significant missing transverse momentum, and a τ lepton reconstructed through its hadronic or leptonic decays. Limits are set on the product of the leptoquark production cross section and branching fraction and interpreted as exclusions in the plane of the leptoquark mass and the leptoquark-τ-quark coupling strength.

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Leptoquarks (LQs) are hypothetical color-triplet bosons carrying both baryon and lepton numbers and having fractional electric charge [1–6]. Mechanisms involving LQs coupled to third-generation quarks and leptons could explain the deviations from standard model predictions observed in several measurements of B meson decays, as explained in Refs. [7–10] and references therein.

At the CERN LHC, LQs can be produced singly through quark-gluon fusion, in pairs through gluon fusion or quark-antiquark annihilation, as part of the nonresonant production of two leptons in the t-channel, or from lepton-quark collisions. While the ATLAS and CMS Collaborations have performed searches for LQs targeting the first three production mechanisms [11–17], the last production mode has never been explored at the LHC. Recent theoretical progress in the determination of the lepton and photon density functions in the proton [18], based on the LUX approach [19,20], has shown that a significant LQ production cross section can be expected in proton-proton (pp) collisions [21–24].

Lepton-induced production of LQs proceeds via the collision of a lepton and a quark, where the lepton is produced through a photon via quantum fluctuations in the proton. A leading-order Feynman diagram for this process is shown in Fig. 1. After the decay of the LQ, the final state consists of a high transverse momentum (p_{T}) centrally produced lepton from the LQ decay, a same-flavor opposite-sign forward lepton from the photon decay, and a high-p_{T} centrally produced jet from the LQ decay. The forward lepton in this production mode usually has p_{T} below reconstruction threshold and differs from other production modes, which typically have two high-p_{T} leptons. This Letter presents the first search for scalar LQs produced in τ-lepton–quark collisions. For the strongest experimental sensitivity, we consider couplings to light-flavor (u, d, and s) and b quarks. The search is based on pp collision data at $\sqrt{s} = 13$ TeV collected with the CMS detector in 2016–2018 corresponding to an integrated luminosity of 138 fb^{-1}. Three different decay modes of the τ lepton are studied, resulting in the $\tau_{\mathrm{h}} + \mathrm{jet}$, $e + \mathrm{jet}$, and $\mu + \mathrm{jet}$ final states, where τ_{h} denotes a τ lepton decaying hadronically. Tabulated results are provided in the HEPData record for this analysis [25].

The CMS apparatus [26] is a multipurpose, nearly hermetic detector, designed to trigger on [27,28] and identify electrons, muons, photons, and both charged and neutral hadrons [29–31]. A global "particle-flow" (PF) algorithm [32] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic, and a brass and scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build τ leptons, jets, and missing transverse momentum ($\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$) [33–36].

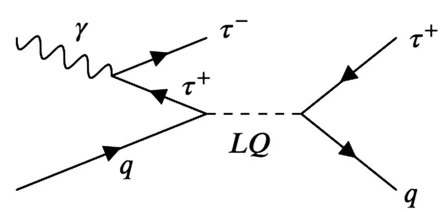

FIG. 1. Feynman diagram of the lepton-induced LQ production.

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The signal and some of the background contributions are estimated using simulations. Signal samples for scalar LQs in the s-channel single LQ production are generated at next-to-leading-order (NLO) with POWHEG interfaced with HERWIG [37] for the showering, using the models and LUXlep lepton parton distribution functions (PDFs) described in Refs. [18,21]. The LUXlep PDF set results from the combination of the NNPDF3.1luxQED set [38] and the lepton PDFs of Ref. [18], which are obtained with a framework similar to that used to determine the PDFs of the photon in the proton using electron-proton scattering data [19,20]. The signal samples are generated for $b\tau$ ($u\tau$) couplings, for LQ masses m_{LQ} between 0.6 and 2.0 (0.6 and 3.0) TeV, an absolute electric charge of $2/3e$ ($1/3e$), and a Yukawa coupling at the LQ-lepton–quark vertex, λ, between 0.5 and 3.0 (0.2 and 2.0). Charge conjugate pairs are simulated together. The analysis acceptance and efficiency, determined from simulation, are similar for couplings to any light-flavor quark, and the samples with LQ-u-τ couplings are also used to extract results on LQ-d-τ and LQ-s-τ couplings. Results on LQ-c-τ couplings cannot be extracted from the same simulation because events with such couplings have a different efficiency for the requirement on the identification of jets originating from b quarks, which is used to build analysis categories as described later.

The cross sections for all coupling hypotheses are computed at NLO [23,24]. The MadGraph5_aMC@NLO 2.6.5 event generator [39] is used to generate events originating from $Z+\mathrm{jets}$ and $W+\mathrm{jets}$ processes. They are simulated at NLO with the FxFx jet matching and merging [40]. The vector boson p_{T} distribution is corrected to match a calculation at next-to-NLO (NNLO) for strong interactions and NLO with the next-to-leading logarithmic Sudakov approximation for electroweak interactions [41]. The MadGraph5_aMC@NLO generator is also used for the simulation of diboson production, while POWHEG 2.0 [42–46] is used for $t\bar{t}$ and single top quark production. The generators are interfaced with PYTHIA 8.240 [47] to model the parton showering, fragmentation, and hadronization, as well as the decay of the τ leptons. The PYTHIA parameters affecting the description of the underlying event are set to the CP5 tune [48]. The NNPDF3.1 PDF set [49–51] at NNLO precision is used for background simulations. Additional pp interactions per bunch crossing are added to the simulated samples with the frequency distribution matching that observed in data. Generated events are processed through a GEANT4 [52] simulation of the CMS detector.

Electrons are reconstructed from energy deposits in the calorimeters and tracks in the tracking system, and identified with a cut-based discriminant [29]. Muons are reconstructed from tracks and hits in the tracker and muon systems [30,53]. Jets are clustered from PF candidates using the anti-k_{T} FASTJET algorithm with a distance parameter R of 0.4 [54,55]. Their energy is corrected on an event-by-event basis [56]. Jets originating from b quarks are identified with the medium working point of the DeepJet algorithm [57,58]. The decay products of τ leptons decaying hadronically are reconstructed with the hadrons-plus-strips algorithm [33]. Quark and gluon jets, electrons, and muons misidentified as τ_{h} candidates are reduced with deep neural network discriminants [36]. The tight working point is used to separate τ_{h} candidates from jets; its efficiency is about 75% for τ_{h} with $p_{\mathrm{T}} > 100$ GeV [36]. The loosest working point, used in the background estimation procedure, has an efficiency above 98%. The vector $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is defined as the projection onto the plane perpendicular to the beam axis of the negative vector momentum sum of all reconstructed PF objects in an event. Its magnitude is referred to as $p_{\mathrm{T}}^{\mathrm{miss}}$.

The selection of events in the $\tau_{\mathrm{h}}+\mathrm{jet}$ final state relies either on a single τ_{h} trigger with online thresholds ranging from 140 to 180 GeV, depending on the data-taking year, or on a trigger requiring the scalar p_{T} sum of jets in the event with $p_{\mathrm{T}} > 40$ GeV to be above 900–1050 GeV. Events are selected in the $e+\mathrm{jet}$ final state using a single isolated electron trigger with online thresholds in the range of 27–35 GeV complemented with a photon trigger for $p_{\mathrm{T}} > 175$–200 GeV. In the $\mu+\mathrm{jet}$ final state, single muon triggers with online thresholds between 24 and 50 GeV are used. Depending on whether the jet is tagged as originating from a b quark [57,58], the event is classified to be in a “btag” or “no-btag” category. A significant $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ satisfying $|\Delta\phi(\ell,\vec{p}_{\mathrm{T}}^{\mathrm{miss}})| < 0.2$–0.3 is required, where ℓ stands for the visible decay products of the τ lepton, as expected from the presence of one or more neutrinos in the τ lepton decay. The off-line selection criteria for the lepton, leading jet, and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ are presented in Table I. They differ slightly for final states with leptonically and hadronically decaying τ leptons because of the different background contributions, triggers, and fractions of visible τ lepton momentum. To select the LQ production mechanism targeted in this analysis, events are discarded if a second well-identified and isolated electron, muon, or τ_{h} candidate with $p_{\mathrm{T}} > 50$ GeV and absolute pseudorapidity, $|\eta|$, less than 2.1 is found. This additional lepton veto removes about 5% of the signal

TABLE I. Selection criteria per final state.

Variable	$\tau_{\mathrm{h}}+\mathrm{jet}$	$e+\mathrm{jet}$	$\mu+\mathrm{jet}$
p_{T}^{ℓ} (GeV)	> 200	> 100	> 100
$\lvert\eta^{\ell}\rvert$	< 2.1	< 2.1	< 2.1
$p_{\mathrm{T}}^{\mathrm{jet}}$ (GeV)	> 300	> 200	> 200
$\lvert\eta^{\mathrm{jet}}\rvert$	< 2.4	< 2.4	< 2.4
$p_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	> 100	> 150	> 150
$p_{\mathrm{T}}(\vec{\ell}+\vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ (GeV)	> 100	> 100	> 100
$\lvert\Delta\phi(\ell,\vec{p}_{\mathrm{T}}^{\mathrm{miss}})\rvert$ (radians)	< 0.3	< 0.2	< 0.2
$\Delta R(\ell,\mathrm{jet})$	> 0.5	> 0.5	> 0.5

events in simulation. With this veto, other LQ production modes contribute less than 1% to the signal yield and are neglected.

As an estimation of m_{LQ} at reconstruction level, we calculate the collinear mass, defined as $m_{\mathrm{coll}} = m_{\mathrm{vis}}(\tau, \mathrm{jet})/\sqrt{x_{\mathrm{vis}}}$, where $m_{\mathrm{vis}}(\tau, \mathrm{jet})$ is the invariant mass of the visible τ decay products and the jet, $x_{\mathrm{vis}} = p_{\mathrm{T}}^{\mathrm{vis}}(\tau)/[p_{\mathrm{T}}^{\mathrm{vis}}(\tau) + p_{\mathrm{T}}^{\mathrm{invis}}(\tau)]$, and $p_{\mathrm{T}}^{\mathrm{invis}}(\tau)$ is the component of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ in the direction of the visible τ decay products. This calculation assumes that the neutrinos from τ lepton decays are the only source of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and have the same η as the visible τ decay products. The experimental resolution on m_{coll} is about 5%–10%, depending on the final state and m_{LQ}, and for $\lambda \lesssim 1$ the natural width of the signal is negligible by comparison. In simulated events, the m_{coll} distribution peaks at the generated m_{LQ} values.

Background events with a prompt lepton in the final state (W + jets, Drell-Yan, diboson, single top quark, and $t\bar{t}$ production events) are estimated from simulation and normalized to their theoretical cross sections [59–64], with the exception of the normalization of W + jets events in the btag categories. Because of the lack of a precise prediction for the cross section of W + jets in association with heavy-flavor jets, the latter is extracted from data in control regions (CRs) in the e + jet and μ + jet final states with $0.2 < |\Delta\phi(\ell, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})| < 0.4$, where ϕ is the azimuthal angle in radians. The variable N_{jets}, defined as the number of jets with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.4$, and separated by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.5$ from the selected lepton, is used as an observable to separate W + jets from $t\bar{t}$ events, which on average have a higher number of jets. After the maximum likelihood fit including the signal regions (SRs), described later, the cross section for the W + jets background in the btag categories is measured to be $1.04^{+0.07}_{-0.06}$ times the prediction from simulation, using the inclusive W + jets cross section at NNLO [59].

The backgrounds with a jet misidentified as a τ_{h} candidate (an electron or muon), dominated by QCD multijet events, constitute about 50% (10%) of the total background and are estimated from data. The probability for jets selected with the loosest working point of the τ_{h} discriminator to pass the tighter identification requirements in the signal region, called the misidentification factor (MF), is measured as a function of $p_{\mathrm{T}}(\tau_{\mathrm{h}})$, N_{jets}, $|\eta|$, and jet p_{T}. It is in the range 0.10–0.25. This measurement is performed in a CR with a selection identical to that in the signal region, except that the $p_{\mathrm{T}}^{\mathrm{miss}}$ requirement is inverted. A multiplicative correction for the extrapolation to higher $p_{\mathrm{T}}^{\mathrm{miss}}$ values in the SR is applied. The MF for electrons is measured as a function of the electron p_{T} because the trigger requirements are p_{T}-dependent, while the muon MF is measured as a function of $p_{\mathrm{T}}^{\mathrm{miss}}$, since the relative fraction of QCD multijet and W + jets backgrounds varies with $p_{\mathrm{T}}^{\mathrm{miss}}$. The observed $p_{\mathrm{T}}^{\mathrm{miss}}$ linear dependence is extrapolated to the SR for $150 < p_{\mathrm{T}}^{\mathrm{miss}} < 300$ GeV and is assumed constant above 300 GeV. Events that pass the SR selection with the exception of the τ_{h}, electron, or muon identification, depending on the final state, are reweighted using the MFs to estimate the background with misidentified jets. Contributions from prompt τ_{h} candidates, electrons, or muons in this region are estimated from simulation and subtracted to avoid double counting events containing genuine leptons.

After the application of the selection criteria shown in Table I, boosted decision trees (BDTs) are trained with the TMVA package [65] for each final state to improve the separation between the signal and background. The input variables, chosen to have a limited dependence on m_{LQ}, are the following: $|\Delta\phi|$ between pairs of analysis objects (electrons, muons, τ_{h}, jets, $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$), the ratio of the objects' p_{T} to m_{coll} or to each other's p_{T}, the ΔR separation between the jet and the reconstructed τ lepton, and N_{jets}. The BDTs are trained with a mixture of all signal samples with various m_{LQ} and λ, against background events coming from W + jets production and either processes with misidentified jets in the τ_{h} + jet channel, or $t\bar{t}$ events in the e + jet and μ + jet channels. The BDT training is performed once for each final state, and is used in the btag and no-btag categories, for all data-taking years and m_{LQ} hypotheses. The BDT output distribution is verified to be well predicted in a validation region where the requirement on $|\Delta\phi(\ell, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})|$ is inverted.

Events in the no-btag (btag) category are further split into 4 (3) subcategories on the basis of their BDT output. In the btag subcategories, events with $N_{\mathrm{jets}} > 2$ are vetoed to reduce the contribution from the $t\bar{t}$ background. The discriminating observable is m_{coll} in all subcategories and final states.

Uncertainties in the reconstruction, identification, and isolation of τ_{h} candidates (electrons, muons) are determined via the "tag-and-probe" method [66] and can be as high as 15% (2%, 2%). The b tagging uncertainties for heavy-flavor jets and mistagging uncertainties for light-flavor quark and gluon jets are included with partial correlations between the data-taking years. They are in the range 6%–9% in the btag category for LQs coupled to b quarks. The uncertainty in the efficiency of the τ_{h} (electron, muon) trigger ranges up to 11% (2%, 2%). The uncertainty in the energy scale of τ_{h} candidates is below the percent level for all τ_{h} decay modes, and is propagated to the m_{coll} distributions. The impact of uncertainties in the energy scale and resolution of jets, and in the measurement of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, is smaller by comparison. The uncertainties in the energy scale of electrons and muons are negligible as compared with the uncertainties mentioned above.

The uncertainties in the $t\bar{t}$, diboson, and single top quark production cross sections are 5.2%, 2.5%, and 3.7%, respectively [61–64]. The uncertainties in the NNLO cross sections of the Z + jets and W + jets backgrounds are 2%

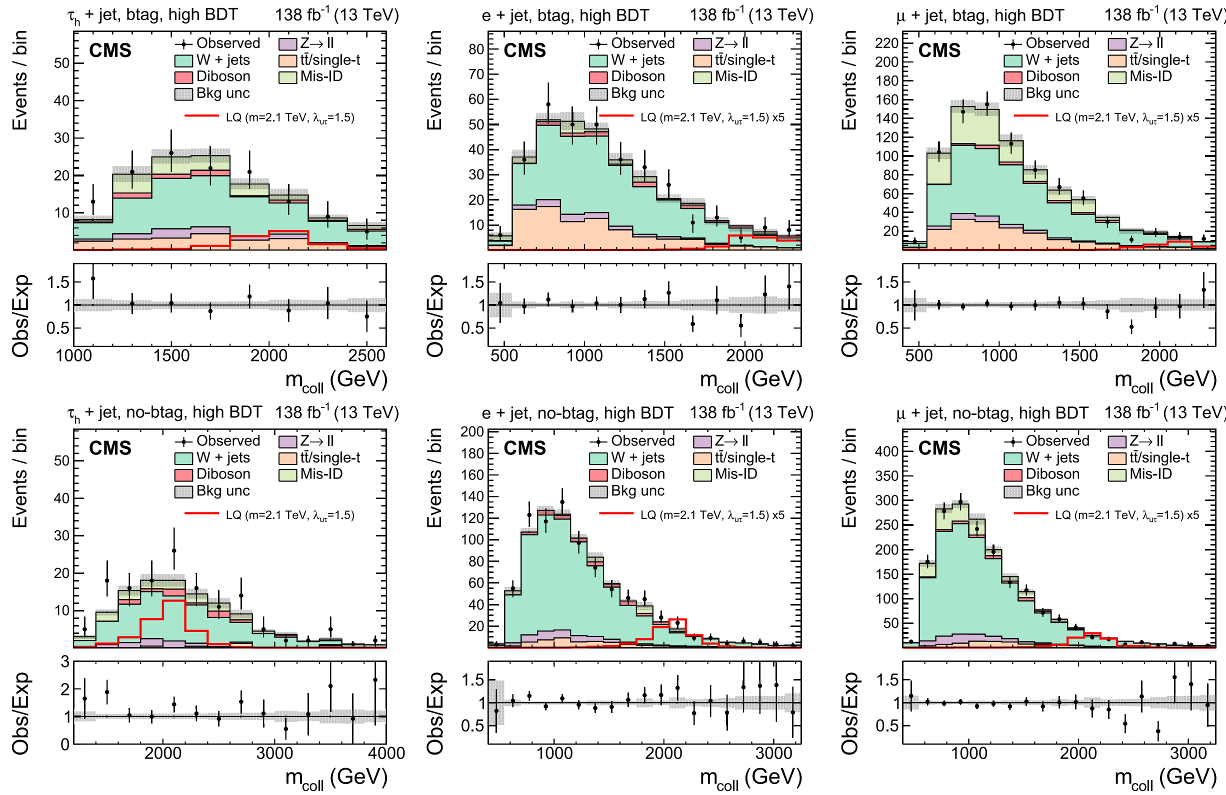

FIG. 2. Observed and expected distributions of m_{coll} in the $\tau_{\mathrm{h}}+\mathrm{jet}$ (left), $e+\mathrm{jet}$ (center), and $\mu+\mathrm{jet}$ (right) channels for the btag (upper) and no-btag (lower) subcategories with the BDT requirements selecting the most signal-like events. The bands include statistical and systematic uncertainties. The background distributions are the results of the maximum likelihood fit. For clarity, the signal distributions in the $e+\mathrm{jet}$ and $\mu+\mathrm{jet}$ final states are multiplied by a factor of 5.

and 3%, respectively [59,60]. In the btag category, the $Z+\mathrm{jets}$ background normalization uncertainty is increased to 20% on the basis of the agreement observed in a CR with 2 τ_{h} candidates and 1 b tagged jet, while the normalization of the $W+\mathrm{jets}$ background is left floating in the fit, resulting in an uncertainty of 7% as detailed above. The acceptance uncertainties in the renormalization and factorization scales, PDFs, and parton showering for these simulated processes are also included. For the signal, uncertainties in the renormalization and factorization scales, and in the PDFs are included. They affect the m_{coll} distributions and have a normalization effect in the ranges 3%–4% (4%–6%) (scales) and 2%–3% (2%–4%) (PDFs), respectively, for LQs with $u\tau$ ($b\tau$) couplings, in the mass ranges considered in the analysis [23]. The uncertainty in the integrated luminosity is 1.6% [67–69].

Different uncertainties affecting the m_{coll} distributions are considered for the background with jets misidentified as τ_{h} candidates: 10% uncertainty per detector region (barrel or end caps), 10% uncertainty per N_{jets} bin, 30% uncertainty for events with $p_{\mathrm{T}}(\tau_{\mathrm{h}}) > 600$ GeV, 10% uncertainty in the leading jet p_{T} correction, and the $p_{\mathrm{T}}^{\mathrm{miss}}$ correction uncertainty described earlier. The uncertainty in the MFs for electrons and muons originates from the limited number of events in the measurement and from the choice of observables and selection criteria. It results in a 20% normalization uncertainty for backgrounds with misidentified electrons or muons, uncorrelated between the data-taking years. In the $\mu+\mathrm{jet}$ channel, an uncertainty in the $p_{\mathrm{T}}^{\mathrm{miss}}$ dependence is included.

A maximum likelihood fit is performed with the signal normalization as a free parameter, and the systematic uncertainties described above as nuisance parameters. The m_{coll} distributions in the different subcategories and final states are fitted simultaneously, together with the N_{jets} distributions in the CRs that control the normalization of the background from $W+\mathrm{jets}$ with a b tagged jet. Those with the highest BDT output requirement, selecting the most signal-like events, are shown in Fig. 2. The btag subcategory with the highest BDT output requirement contains about 70% (41%, 56%) of the LQ events with $m_{\mathrm{LQ}}=2$ TeV and $\lambda_{b\tau}=1.0$ entering the btag category, and about 9.8% (5.6%, 12%) of the total background in the $\tau_{\mathrm{h}}+\mathrm{jet}$ ($e+\mathrm{jet}$, $\mu+\mathrm{jet}$) final state. The no-btag subcategory with the highest BDT output requirement contains about 55% (30%, 33%) of the LQ events with $m_{\mathrm{LQ}}=3$ TeV and $\lambda_{u\tau}=1.0$ entering the no-btag category, and about 0.86% (1.1%, 1.9%) of the total background in the no-btag category in the $\tau_{\mathrm{h}}+\mathrm{jet}$ ($e+\mathrm{jet}$, $\mu+\mathrm{jet}$) final state.

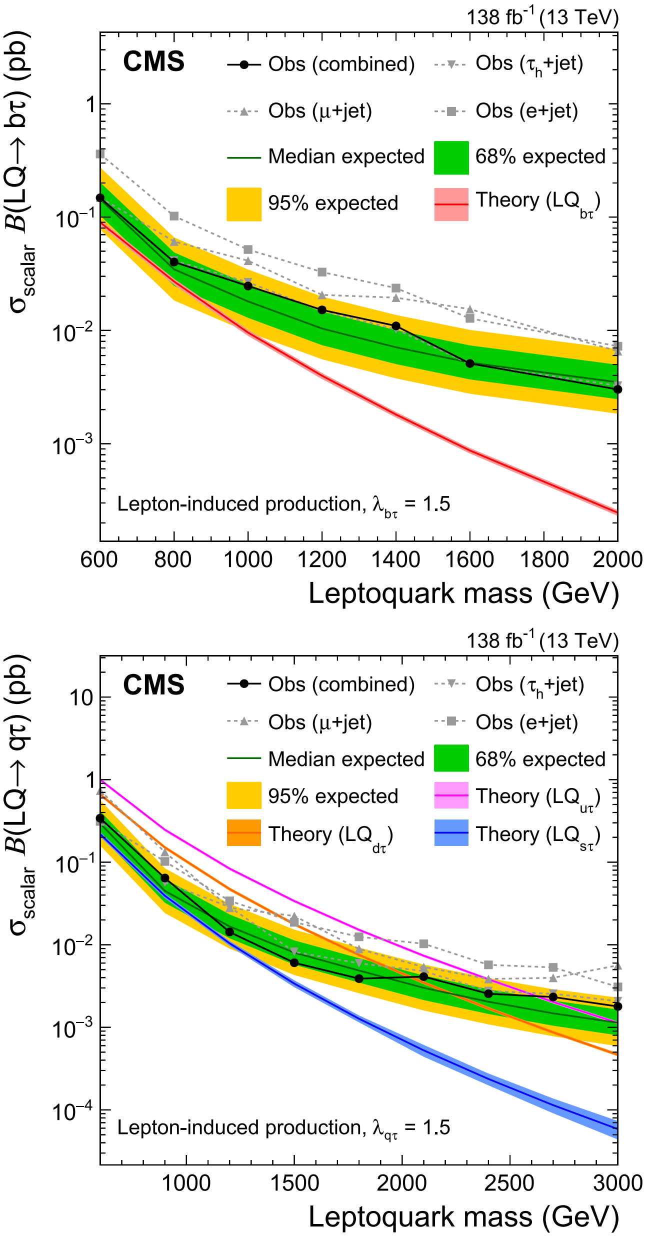

FIG. 3. Expected and observed upper limits at 95% C.L. on the product of the scalar lepton-induced LQ production cross section and the branching fraction for a LQ coupled to b quarks and τ leptons (left), or to light-flavor quarks and τ leptons (right), using $\lambda = 1.5$. The theoretical cross sections correspond to the calculations of Refs. [23,24]. The inner (green) band and the outer (yellow) band indicate the regions containing 68% and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The filled circles show the observed limits for the combination of final states, while the other markers indicate the observed results per final state.

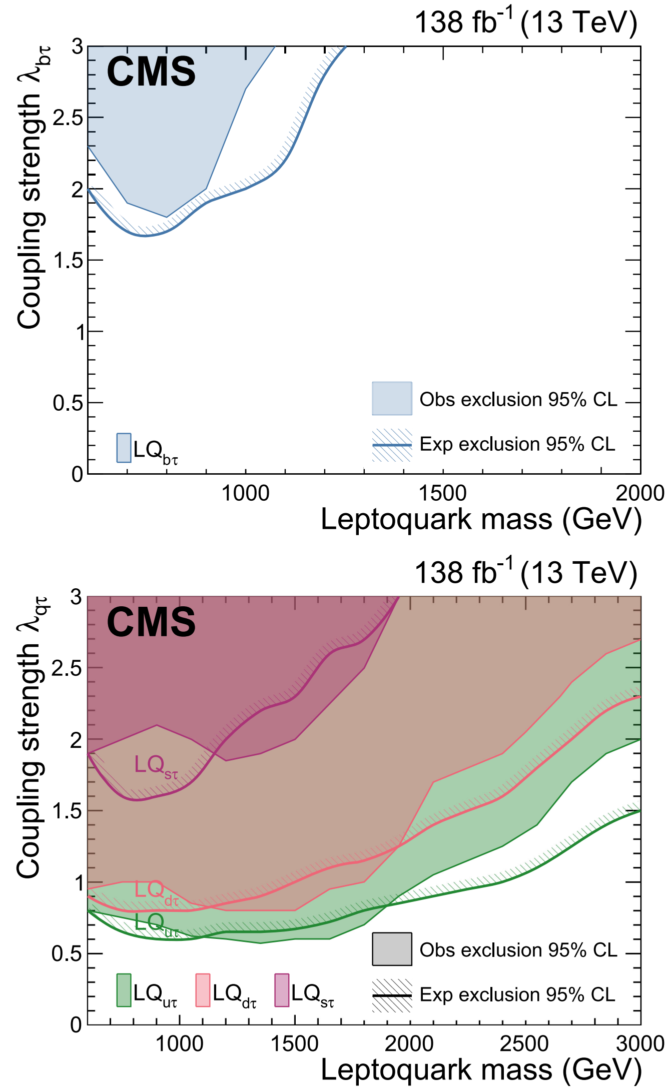

FIG. 4. Upper limit at 95% C.L. on the coupling strength λ of a scalar LQ to b quarks and τ leptons (upper), and to light-flavor quarks and τ leptons (lower). Regions above the hatched lines correspond to the expected exclusions.

No statistically significant excess above the standard model backgrounds is observed. Upper limits at 95% confidence level (C.L.) are set on the product of the LQ production cross section and the branching fraction for different coupling hypotheses, using the C.L.$_s$ method [70,71] in the asymptotic approximation [72]. Because of the trigger requirements, the signal acceptance in the τ_h + jet final state is low for $m_{LQ} = 600$ GeV and the limits for this mass point are derived from the distributions in the e + jet and μ + jet final states only. The 95% C.L. limits are in the range 0.34–0.0018 pb (0.15–0.0030 pb) for masses between 0.6 and 3.0 TeV (0.6 and 2.0 TeV) for $\lambda_{u\tau} = 1.5$ ($\lambda_{b\tau} = 1.5$), as shown in Fig. 3. The limits are translated into exclusion regions in the m_{LQ}-λ plane, as shown in Fig. 4, assuming the branching fraction of the LQs to a quark and a τ lepton to be 100% for the considered quark flavor. The observed limits on LQs coupling to b quarks and τ leptons extend existing constraints from searches in other production modes at high m_{LQ} [12]. Leptoquarks coupling to light-flavor quarks and τ leptons can be excluded at masses above the previously existing limit of 1.3 TeV [17], for $\lambda_{u\tau}$ ($\lambda_{d\tau}$, $\lambda_{s\tau}$) above 0.6 (0.8, 1.9).

In summary, a search for leptoquarks produced in lepton-quark collisions and coupled to τ leptons has been performed for the first time, using data collected with the CMS detector in 2016–2018. These limits are complementary to those set using other production modes at high mass and coupling values for $b\tau$ couplings, while the limits on the couplings of leptoquarks to light-flavor quarks extend the mass range excluded by previous searches in other production modes.

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 and other centers 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, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (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); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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