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Search for t-channel scalar and vector leptoquark exchange in the high-mass dimuon and dielectron spectra in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract: A search for t-channel exchange of leptoquarks (LQs) is performed in dimuon and dielectron spectra using proton-proton collision data collected at $\sqrt{s} = 13$ TeV with the CMS detector at the CERN LHC. The data correspond to an integrated luminosity of 138 fb^{-1}. Eight scenarios are considered, in which up or down quarks couple to muons or electrons via a scalar or vector LQ exchange, for dilepton invariant masses above 500 GeV. The LQ masses are probed up to 5 TeV, beyond a regime probed by previous pair-production and single-production searches. The differential distributions of dilepton events are fit to templates that model the nonresonant LQ exchange and various standard model background processes. Limits are set on LQ-fermion coupling strengths for scalar and vector LQ masses in the 1–5 TeV range at 95% confidence level, establishing stringent limits on first- and second-generation LQs.

Keywords: Beyond Standard Model, Hadron-Hadron Scattering, Lepton Production

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1 Introduction

Leptoquarks (LQs) are hypothetical particles proposed to explain the similarities between the quark and lepton sectors of the standard model (SM). Leptoquarks were initially introduced in early extensions of the SM, for example, in grand unified theories based on the SU(5) and SO(10) groups [1–6], such as the Pati-Salam model [1], composite models [7, 8], and technicolor models [9–11]. Leptoquarks have also been proposed as mediators of interactions between SM and dark matter particles [12, 13], and appear in R-parity violating supersymmetry models [14]. Results from the Muon $g-2$ experiment in 2021 showed deviations in the experimental value of the anomalous magnetic moment of the muon to 0.46 ppm [15]. The deviation is reduced when updated lattice quantum chromodynamics (QCD) calculations are considered [16]. Although the tension of the $g-2$ measurements has been largely resolved by using these calculations, a massive LQ could contribute to the anomalous magnetic moment by mixing with the SM Higgs field [17], and thus move the theory even closer to the latest experimental result [18].

Leptoquarks are electrically charged, color-triplet bosons, either scalar or vector, that carry a baryon number (B), as well as a lepton number (L). They have a fermion number $F = 3B + L$ of 0 or -2; however, LQs with $F = -2$ can mediate proton decay, and stringent limits from dedicated proton decay searches have strongly constrained such LQs [19]. Distinctions between different LQs are based on their SM gauge group transformation

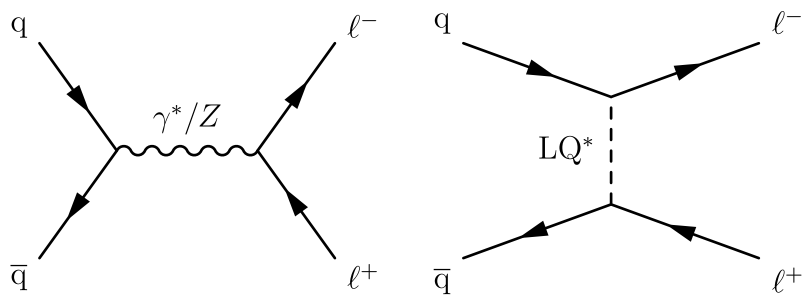

Figure 1. Leading order Feynman diagrams for SM DY production (left) and t-channel LQ exchange (right). The LQ amplitude interferes with the Z/γ^* amplitude.

properties, giving rise to twelve LQ multiplets. Only six families do not mediate proton decay. Leptoquarks are labeled as first-, second-, third-, or mixed-generation based on the SM quarks and leptons with which they interact.

The quark-LQ-lepton interaction is characterized by the LQ-fermion coupling constants y_{LQ} (g_{LQ}) for the scalar (vector) case. At colliders, LQs can be produced singly or in pairs, or manifest via t-channel exchange. The pair-production channel is dominated by gluon-gluon fusion, with a cross section proportional to the square of the strong coupling constant (α_S^2). Since this production mode proceeds via the strong interaction, it is insensitive to the LQ-fermion coupling, and results in the most stringent bounds at low LQ masses ($m_{\mathrm{LQ}} \sim 1\,\mathrm{TeV}$). The single-production cross section scales as $\alpha_S y_{\mathrm{LQ}}^2$ ($\alpha_S g_{\mathrm{LQ}}^2$), but the channel can be more sensitive than pair production at higher m_{LQ} or y_{LQ} (g_{LQ}). Finally, the t-channel exchange process, shown in figure 1, has a cross section proportional to y_{LQ}^4 (g_{LQ}^4), with additional contributions proportional to y_{LQ}^2 (g_{LQ}^2) from the interference with dilepton production via the Drell-Yan (DY) process. This channel can have superior sensitivity at even higher m_{LQ}, as its cross section decreases more slowly than for the other two channels, as a function of m_{LQ}.

Several searches for LQs have been performed by the ATLAS and CMS Collaborations. Third-generation scalar and vector LQs coupled to a tau (τ) lepton and a bottom (b) quark were studied in refs. [20, 21], which considered single and pair production, as well as t-channel LQ exchange. The t-channel exchange process is the most sensitive channel at large m_{LQ} and y_{LQ} (g_{LQ}), excluding at 95% confidence level (CL) third-generation scalar (vector) LQs with masses of 0.5–1.5 (0.5–2.3) TeV for y_{LQ} (g_{LQ}) values larger than 1.8–3.5 (0.9–3.5). Searches for vector LQs in the $\tau\tau$ channel were reported in ref. [22], in which m_{LQ} of 1–5 TeV were excluded for $g_{\mathrm{LQ}} > 0.8$–3.7 at 95% CL for a U_1 LQ in the Pati-Salam model.

For pair-produced scalar LQs coupled to first- and second-generation fermions, the most stringent limits have been set by ATLAS, excluding LQs with masses below 1.8 and 1.7 TeV at 95% CL, respectively, independent of y_{LQ} and assuming a branching fraction of 100% into a quark and a lepton [23]. Single production of first- and second-generation scalar LQs has been studied by CMS [24], in which m_{LQ} below 1.73 TeV and 530 GeV, respectively, were excluded, assuming $g_{\mathrm{LQ}} = 1$ and a branching fraction of 100% into a quark and a lepton. Pair production of first- and second-generation scalar LQs have also been studied by CMS [25, 26]. First-generation scalar m_{LQ} were excluded up to 1.44 TeV at 95% CL, and second-generation scalar m_{LQ} were excluded up to 1.53 TeV, independent of y_{LQ} and assuming a branching

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LQ family	(SU(3), SU(2), U(1))	Spin	Charge
R_2	(3, 2, 7/6)	0	5/3, 2/3
$\widetilde{R}_2$	(3, 2, 1/6)	0	2/3, -1/3
U_3	(3, 3, 2/3)	1	5/3, 2/3, -1/3

Table 1. Properties of the R_2, $\widetilde{R}_2$, and U_3 LQs from ref. [19]. This paper describes a search for R_2 LQs with RL couplings and charge 5/3, $\widetilde{R}_2$ LQs with RL couplings and charge 2/3, and U_3 LQs with charges 2/3 and 5/3.

fraction of 100% into a quark and a lepton. The CMS Collaboration has also studied pair production of first- and second-generation vector LQs, leading to exclusions of m_{LQ} up to 1.5 (1.3) TeV assuming Yang-Mills (minimal) couplings, and m_{LQ} less than 1.7 (1.1) TeV assuming minimal-minimal (absolute minimal) couplings, for a branching fraction of 100% into a quark and a lepton [27].

Motivated by the phenomenological studies performed in refs. [28, 29], three families of LQs are considered: two scalar doublet families, R_2 and $\widetilde{R}_2$, and one vector triplet family, U_3. The subscripts refer to the dimensionality of the SU(2) representation. Within the R_2, $\widetilde{R}_2$, and U_3 families, first- and mixed-generation LQs that couple up and down quarks to electrons and muons are considered. For the scalar doublet families, following ref. [28], the case where the LQ couples only to right-handed quark multiplets and left-handed lepton multiplets (RL) is considered. The LQs are assumed to couple to a single quark and lepton, resulting in four scalar LQ coupling scenarios: two R_2 LQs, $\mathrm{S_{eu}}$ and $\mathrm{S_{\mu u}}$, and two $\widetilde{R}_2$ LQs, $\mathrm{S_{ed}}$ and $\mathrm{S_{\mu d}}$, where the subscripts denote the SM fermions. Similarly, four U_3 vector LQs are considered: $\mathrm{V_{eu}}$, $\mathrm{V_{\mu u}}$, $\mathrm{V_{ed}}$, and $\mathrm{V_{\mu d}}$. The SM gauge group transformation properties for the chosen LQ models are summarized in table 1. The R_2 LQs appear in potential solutions to the muon anomalous magnetic moment problem [30, 31], $\widetilde{R}_2$ LQs appear in beyond-the-SM extensions for lepton flavor universality violation involving sterile neutrinos [31, 32], and U_3 LQs appear in models that describe scenarios for lepton flavor violation [33].

The LQ-quark-lepton interactions are defined by the following terms in the Lagrangian:

$$\mathcal{L} \supset y_{\ell \mathrm{u}} \overline{\mathrm{u}}_R \ell_L R^{5/3} + y_{\ell \mathrm{d}} \overline{\mathrm{d}}_R \ell_L \widetilde{R}^{2/3} + g_{\ell \mathrm{u}} \overline{\mathrm{u}}_L \gamma^{\mu} \ell_L U_{\mu}^{5/3} + g_{\ell \mathrm{d}} \overline{\mathrm{d}}_L \gamma^{\mu} \ell_L U_{\mu}^{2/3} + \text{h.c.}, \tag{1.1}$$

where $y_{\ell \mathrm{u}}$ ($y_{\ell \mathrm{d}}$) are the couplings of the charge 5/3 (2/3) R_2 ($\widetilde{R}_2$) scalar LQs to fermions and $g_{\ell \mathrm{u}}$ ($g_{\ell \mathrm{d}}$) are the couplings of the charge 5/3 (2/3) vector U_3 LQs to fermions. The terms describing couplings of LQs to neutrinos are omitted. A complete description of the LQ interactions, as well as a more detailed review of LQ physics in precision experiments, can be found in ref. [19].

This paper describes the first search for the t-channel exchange of LQs coupled to first- and second-generation SM fermions, probing scalar and vector LQs with masses in the range 1–5 TeV. The search uses proton-proton (pp) collision data at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 138 fb^{-1}, collected by the CMS experiment at the CERN LHC in 2016–2018. The hypothetical signal process results in the nonresonant exchange of muon or electron pairs. It is distinguished from the dominant background of SM DY events using the differential distributions of the dilepton invariant mass, the angle between the incoming quark and the outgoing lepton, and the rapidity of the dilepton system. The observed dilepton distributions are fit with a combination of signal and background templates, both produced by reweighting simulated SM DY events.

The paper is divided into ten sections. The analysis strategy is discussed in section 2, followed by a description of the CMS detector and event reconstruction in section 3. The simulated samples used for the signal and background estimation are described in section 4, and the criteria used to select dimuon and dielectron events are described in section 5. Section 6 contains a detailed discussion of the various backgrounds for this search, and how they are estimated. The procedure to build templates of the signal and background distributions is described in section 7, followed by a discussion of the various systematic uncertainties that affect the measurements in section 8. The results of maximum likelihood fits to data are discussed in section 9, along with the limits at 95% CL on eight LQ couplings as functions of m_{LQ}. Finally, the paper is summarized in section 10.

Tabulated results are provided in the HEPData record for this analysis [34].

2 Analysis strategy

The t-channel LQ exchange occurs in conjunction with the SM DY process, which is the primary background for this search. This analysis utilizes three variables computed from the dilepton system: the invariant mass, $m_{\ell\ell}$; the rapidity y; and $\cos\theta^*$ (abbreviated as c_*), the cosine of the angle between the quark (as opposed to the antiquark) and the lepton (as opposed to the antilepton) in the Collins-Soper frame (dilepton rest frame) [35, 36]. At a pp collider, the direction of the incident quark is unknown. Instead, an approximation is used, defined as $\cos\theta_{\mathrm{R}} \equiv \frac{p_z}{|p_z|} c_*$, abbreviated as c_{R}, where p_z stands for the longitudinal momentum of the dilepton system. This approximation uses the fact that the quark will typically have higher longitudinal momentum than the antiquark, and hence, the longitudinal momentum of the dilepton system will more often align with that of the quark. The observed distributions in these three variables can be expressed as a convolution of the underlying differential cross section:

$$f(m^{\mathrm{r}}_{\ell\ell}, y^{\mathrm{r}}, c_{\mathrm{R}}) = C \int \mathrm{d}m_{\ell\ell}\, \mathrm{d}y\, \mathrm{d}c_* R(m^{\mathrm{r}}_{\ell\ell}, y^{\mathrm{r}}, c_{\mathrm{R}}; m_{\ell\ell}, y, c_*) \varepsilon(m_{\ell\ell}, y, c_*) \frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\ell}\, \mathrm{d}y\, \mathrm{d}c_*}, \quad (2.1)$$

where the superscript r distinguishes reconstructed variables from generator-level variables, C is a normalization constant, R is a resolution function that incorporates detector resolution and parton shower effects, and ε is an efficiency function. Since the convolution is a linear function of the cross section, σ, the resulting reconstructed distribution can be expressed as a sum of convolutions of different contributions to the total cross section. The linearity allows the expected observation for a given signal hypothesis to be represented as a sum of templates that are individually independent of the parameters of interest. Specifically, the parton-level differential cross section of the SM DY process can be written as:

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}c_*}(m^2_{\ell\ell})\right]_{\mathrm{DY}} \propto \frac{3}{8}\left\{(1 + c_*^2) + A_4 c_* + \frac{A_0}{2}\left(1 - 3c_*^2\right)\right\}, \quad (2.2)$$

where A_4 and A_0 are the standard dimensionless coefficients parametrizing the angular distribution of the DY process [37, 38]. The first two terms correspond to the leading order (LO), and the third term corresponds to next-to-LO (NLO). The coefficients A_0 and A_4 are functions of $m_{\ell\ell}$, the transverse momentum (p_T), and y of the dilepton system. Measurements of A_0 probe higher-order corrections in perturbative QCD, whereas A_4 is directly related to the SM forward-backward asymmetry, $A_{FB} = (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B) = \frac{3}{8}A_4$, where σ_F and σ_B are the cross sections for forward ($c_* > 0$) and backward ($c_* < 0$) events, respectively. A measurement of A_{FB} and A_0 was recently performed by CMS [36].

The LO double-differential cross section for DY production that includes the t-channel exchange of a scalar LQ can be expressed as [28]:

$$\begin{aligned}\frac{d^2\sigma}{dm_{\ell\ell}dc_*} \propto \left[\frac{d^2\sigma}{dm_{\ell\ell}dc_*}\right]_{DY} &+ y_{LQ}^4 N_{pure}^S(m_{\ell\ell}) \left(\frac{1-c_*}{1-c_*+\frac{2m_{LQ}^2}{m_{\ell\ell}^2}}\right)^2 \\ &+ y_{LQ}^2 N_{int}^S(m_{\ell\ell}) \left[\frac{(1-c_*)^2}{1-c_*+\frac{2m_{LQ}^2}{m_{\ell\ell}^2}}\right],\end{aligned} \tag{2.3}$$

and the differential cross section for a vector LQ exchange can be expressed as:

$$\begin{aligned}\frac{d^2\sigma}{dm_{\ell\ell}dc_*} \propto \left[\frac{d^2\sigma}{dm_{\ell\ell}dc_*}\right]_{DY} &+ g_{LQ}^4 N_{pure}^V(m_{\ell\ell}) \left(\frac{1+c_*}{1-c_*+\frac{2m_{LQ}^2}{m_{\ell\ell}^2}}\right)^2 \\ &+ g_{LQ}^2 N_{int}^V(m_{\ell\ell}) \left[\frac{(1+c_*)^2}{1-c_*+\frac{2m_{LQ}^2}{m_{\ell\ell}^2}}\right],\end{aligned} \tag{2.4}$$

where $N_{pure}^{S,V}$ and $N_{int}^{S,V}$ are prefactors that depend on $m_{\ell\ell}$, and the vector and axial-vector couplings of the quark and lepton that couple to the LQ. The first LQ-specific term corresponds to pure t-channel LQ exchange, while the second term corresponds to the interference of the t-channel LQ exchange with the SM Z/γ^* diagram.

Following an approach similar to that of ref. [36], the templates are histograms binned in three variables ($m_{\ell\ell}$, c_R, and y), constructed from simulated SM DY events that are reweighted using functions of the generator-level variables to represent each of the terms in eqs. (2.3) or (2.4). A maximum likelihood fit of a linear combination of the templates to the observed data is performed to extract the signal and background parameters, namely A_0, A_4, and either y_{LQ} or g_{LQ}. The template construction is described in more detail in section 7. Each of the eight combinations of spin and coupling to SM fermions is probed separately.

3 The CMS detector and event reconstruction

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. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, is reported in refs. [39, 40].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [41]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [42].

A particle-flow algorithm [43] aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in section 9.4.1 of ref. [44].

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. The single-muon trigger efficiency exceeds 90% over the full η range, and the efficiency to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured in the silicon tracker results in a relative p_{T} resolution of 1% in the barrel and 3% in the endcaps for muons with $p_{\mathrm{T}} < 100$ GeV, and of better than 7% for muons in the barrel with $p_{\mathrm{T}} < 1$ TeV [45].

The single-electron trigger efficiency is approximately 80% over the full η range, and the efficiency to reconstruct and identify electrons is greater than 65% for electrons with $p_{\mathrm{T}} > 20$ GeV. The momentum resolution for electrons with $p_{\mathrm{T}} \approx 45$ GeV from $\mathrm{Z} \to \mathrm{ee}$ decays ranges from 1.7–4.5%. It is generally better in the barrel region than in the endcaps, and also depends on the bremsstrahlung energy emitted by the electron as it traverses the material in front of the ECAL [46].

Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions, increasing the apparent jet momentum. To mitigate this effect, tracks identified as originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions [47].

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4 Simulated event samples

Various Monte Carlo (MC) event generators are used to simulate the SM background processes. The DY samples are generated at NLO in QCD with up to two extra partons using MadGraph5_aMC@NLO [48] v2.2.2 (v2.6.0) for samples corresponding to the 2016 (2017–2018) data-taking periods. The parton shower, hadronization, and quantum electrodynamics final-state radiation are simulated with pythia v8.226 (v8.230) [49], using the FxFx merging scheme and the underlying event tune CUETP8M1 (CP5) [50, 51]. The NNPDF 3.0 parton distribution functions (PDFs) [52, 53] at NLO accuracy are used for samples corresponding to 2016, and NNPDF 3.1 [54] at next-to-NLO (NNLO) are used for 2017–2018. For consistency, all samples were reweighted to NNPDF 3.0 at NLO.

Additional backgrounds include diboson production (WW, WZ, ZZ), photon-induced dilepton production ($\gamma\gamma \to \ell\ell$), top quark pair production ($t\bar{t}$), and single top quark production in association with a W boson (tW). The $t\bar{t}$ and tW backgrounds are generated at NLO using powheg v2.0 [55–58], and interfaced with pythia v8.226 (v8.230), with the CUETP8M2T4 (CP5) underlying event tune [59] for the 2016 (2017–2018) data-taking period. The diboson background samples are generated at NLO, with $ZZ \to \ell\ell\ell'\ell'$, $ZZ \to \ell\ell\nu\nu$, and $WW \to \ell\nu\ell\nu$ processes generated using powheg [60, 61] and $WZ \to qq\ell\ell$, $WZ \to \ell\ell\ell\nu$, and $ZZ \to qq\ell\ell$ processes generated using MadGraph5_aMC@NLO. All diboson samples are showered using pythia and tune CUETP8M1 (CP5) for the 2016 (2017–2018) data-taking periods. The $t\bar{t}$, tW, and diboson backgrounds use the NNPDF 3.0 (3.1) PDFs for 2016 (2017–2018) data-taking periods. The photon-induced background, $\gamma\gamma \to \ell\ell$, is simulated using the CepGen [62] implementation of LPair [63, 64], interfaced with pythia v6.429 [65], using the Suri-Yennie proton structure function parametrization [66]. This contribution is split into three parts because the interaction at each proton vertex can be either elastic or inelastic.

The cross sections for the WZ and ZZ samples are normalized to the NLO predictions calculated with mcfm 6.6 [67], while the cross sections of the WW samples are normalized to the next-to-next-to-leading-logarithmic accuracy predictions [68]. The total cross section for the $t\bar{t}$ process is normalized to the prediction with NNLO accuracy in QCD and next-to-next-to-leading-logarithmic accuracy for the soft-gluon radiation resummation calculated with Top++ 2.0 [69].

Leptoquark signal samples modeled in the SLQrules package [70] are generated using MadGraph5_aMC@NLO. These samples are used only for cross checks on the LQ template method.

The detector response for all MC samples is simulated using Geant4 [71]. The pileup distribution in simulation is weighted to match the one observed in data.

5 Event selection

Events are required to have two leptons of same flavor and opposite charges. The dimuon and dielectron events are selected by single-muon and single-electron triggers, respectively. Dilepton triggers were not used as they had negligible gains over using single-lepton triggers. The events selected by the triggers are reconstructed and required to satisfy a number of offline requirements. The leading muon and electron p_T requirement is at least 40 GeV. The subleading lepton is required to have $p_{\mathrm{T}} > 15\,\mathrm{GeV}$. All muons are required to be within the acceptance of the muon system ($|\eta| < 2.4$), and all electrons must be within $|\eta| < 2.5$, excluding the barrel-endcap transition region of the ECAL ($1.44 < |\eta| < 1.57$) because the reconstruction of an electron object in this region is not optimal. Additionally, to remove cosmic ray muon induced events, the azimuthal angle (ϕ) between the two muons is required to differ from π by more than 5 mrad.

Each reconstructed muon is required to pass identification criteria that are based on the number of hits observed in the tracker, the response of the muon detectors, and a set of matching criteria between muon track parameters, as measured by the inner tracker and muon detectors. To suppress nonprompt muons coming from heavy-flavor decays, each muon must be isolated from other particles in a cone of size $\Delta R = 0.4$ where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ refers to the distance from the muon to a given track. Further, the sum of the energy deposits of the charged and neutral hadrons divided by the muon track p_{T} within this cone should be less than 0.15. More details on the muon identification and reconstruction used in this analysis can be found in refs. [45, 72].

The reconstructed electron candidates are required to pass identification criteria that are based on electromagnetic shower shape variables. Electrons originating from photon conversions are suppressed by requiring that the candidates have at most one missing inner tracker hit and not be consistent with being part of a conversion pair. Electrons are also required to be isolated from other particles within a cone of $\Delta R = 0.3$. The electron isolation criteria are based on the ratios of the electron p_{T} to the sum of energy deposits associated with the photons or hadrons. More details on the electron reconstruction and identification criteria used in this analysis are described in ref. [46].

Events in the signal region (SR) must have $m_{\ell\ell} > 500\,\mathrm{GeV}$. This requirement suppresses $\mathrm{t\bar{t}}$ and nonprompt backgrounds. Additionally, the requirement has negligible impact on the signal sensitivity for heavy LQs ($m_{\mathrm{LQ}} > 1\,\mathrm{TeV}$), which primarily comes from events with $m_{\ell\ell} > 1\,\mathrm{TeV}$.

6 Backgrounds

The dominant background comes from DY events, and the subdominant background consists of fully leptonic decays of $\mathrm{t\bar{t}}$ events. Backgrounds from tW events, diboson processes, and leptonic decays of $\tau\tau$ originating from the DY process are also included. All of these backgrounds are modeled in simulation with a few corrections based on control samples in data. The estimated event yields of the $\mathrm{t\bar{t}}$, tW, $\tau\tau$, and diboson events are validated in data in a control region (CR) of $\mathrm{e}\mu$ events. A small fraction of the background comes from t-channel photon-induced dilepton production, which is modeled with MC simulation as well. Additionally, events where one or more jets are incorrectly identified as leptons also contribute to the total background yield. Such events are referred to as “MisID” events, primarily arising from W+jets processes and events composed uniquely of jets produced through the strong interaction, referred to as QCD multijet events. A technique based on CRs in data is employed to estimate the MisID contribution. For the dimuon (dielectron) channel, the total background from simulation and CR-based estimation consists of approximately 85 (82)% DY, 10 (9)% $\mathrm{t\bar{t}}$ plus tW, 5 (4)% diboson, and 0.5 (5)% MisID events.

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The MisID background is estimated from data using the "misidentification rate" method [73, 74]. The misidentification rate is defined as the probability of a jet, having been reconstructed as a lepton candidate, to pass the lepton selection requirements outlined in section 5. This rate is measured in a sample with two reconstructed leptons from a Z boson decay and an additional, potentially misidentified lepton. The two leptons corresponding to a Z boson decay are required to pass the lepton identification requirements and have an invariant mass within 7 GeV of the Z boson mass [75]. The third lepton candidate is used as a probe to measure the misidentification rate. This third lepton candidate is required to pass a less stringent set of identification and isolation requirements than the full selection requirements of the analysis. The MisID background can then be estimated from CRs of data events with two lepton candidates: one region in which one lepton fails the full selection requirements, to model the W+jets events, and another region in which both leptons fail the requirements, to model the QCD multijet events. Events from these regions are assigned weights based on the expected misidentification probabilities of the failing lepton candidates. Contamination of this region by lepton pairs from DY and other prompt processes is subtracted using MC simulation. These reweighted events are used to estimate the yield and shape of the MisID background.

The MisID background estimation is validated in a CR with the same selection criteria as the SR, except the lepton pairs are required to have same-sign (SS) rather than opposite-sign (OS) charges. A large fraction of the events in this CR stem from misidentified jets. In the ee channel, there is a significant contribution to this sample from OS DY events where the charge of one of the electrons has been incorrectly assigned. The rate of charge misassignment in simulation is corrected using a sample of dilepton events near the Z peak with $70 < m_{\ell\ell} < 110$ GeV. The MisID background estimate as well as MC estimates of other backgrounds are compared with the observed yield of SS events. A c_{R}-dependent correction to the MisID background estimate is calculated using the ratio of the MisID estimate to the number of observed SS events minus other backgrounds. The uncertainty in this correction is calculated as the quadratic sum of the statistical uncertainties from the limited sample size, the uncertainty in the number of DY pairs reconstructed as SS pairs, as well as a systematic uncertainty reflecting possible differences in shape between SS and OS MisID estimates.

The $\tau\tau$, tW, $\mathrm{t\bar{t}}$, and diboson backgrounds are validated in data using eμ events. The eμ CR has the same selection criteria as the SR, except that events are required to have one muon and one electron rather than pairs of same flavor. The CR is constructed from events that have a leading muon and a subleading electron, because samples with high-quality muons have lower contamination from misidentified leptons. The muon is required to have $p_{\mathrm{T}} > 40$ GeV and pass the single-muon trigger, and the electron is required to have $p_{\mathrm{T}} > 15$ GeV. The identification and isolation criteria for muons and electrons are the same as in the SR. The MisID background is also present in this eμ CR and is estimated using the misidentification rate technique previously described. Good agreement is observed between the simulated and observed yields of eμ events across the entire mass range.

Because diboson events are produced via electroweak processes, they are expected to have a small forward-backward asymmetry in their lepton pairs; $\mathrm{t\bar{t}}$ events are also known to have an asymmetry, but it is too small to be detected using leptons alone [76]. The QCD and

W+jets backgrounds are expected to have no asymmetry. Based on MC and CR estimates, an overall $A_{\mathrm{FB}} \approx 0.01$ is predicted in the region of eμ events. The observed value in the eμ CR is $A_{\mathrm{FB}} = 0.012 \pm 0.003$, consistent with this expectation.

Although the overall normalizations and asymmetries in eμ events are observed to be consistent between data and simulation, there are discrepancies between the predicted and observed shapes of the c_{R} distributions. To address these discrepancies, a correction is derived from the ratio of the c_{R} distributions in data and simulation in eμ events, and applied to the shape of the c_{R} distributions in simulation. Because the asymmetry is modeled well, this correction is derived symmetrically in c_{R} using four bins of $|c_{\mathrm{R}}|$. A single correction is derived in the 500–3000 GeV mass range because of the limited event count. This correction modifies by 5–25% the shapes of the templates used to model the corresponding backgrounds in the SR. The statistical uncertainty in each of the four $|c_{\mathrm{R}}|$ bins is modeled as a separate shape nuisance parameter.

Figure 2 shows a comparison between measured μμ and ee events and the background prediction in the SR after all corrections have been applied. Good agreement is observed between the simulated and observed numbers of μμ and ee events.

7 Template construction

To model the dilepton differential distributions, parameter-independent templates are constructed for each piece of the differential cross section of LQ production shown in eqs. (2.3) and (2.4). For the SM DY component, the differential cross section is reparametrized as follows:

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}c_*}(m_{\ell\ell}^2)\right]_{\mathrm{DY}} \propto \frac{3}{4(2+\alpha)}\left\{(1+c_*^2) + \frac{(2+\alpha)}{2}\, A_4\, c_* + \alpha(1-c_*^2)\right\}, \tag{7.1}$$

where $\alpha = \frac{2A_0}{2-A_0}$. The first two terms are symmetric and antisymmetric in c_*, respectively, and the third term is proportional to α. The LQ exchange comprises two terms with coefficients y_{LQ}^4 or g_{LQ}^4 for the pure exchange of the LQ and, y_{LQ}^2 or g_{LQ}^2 for the interference with Z/γ^*. The templates for these five pieces of the cross section are denoted as f_{s} (symmetric), f_{a} (antisymmetric), and f_α (corresponding to the third term) for the three DY templates and $f_{\mathrm{LQ(pure)}}$ and $f_{\mathrm{LQ(int)}}$ for the pure and interference LQ terms, respectively.

In ref. [36], the f_{s}, f_{a}, and f_α templates are constructed by binning events in c_{R} and reconstructed $|y|$. These templates are constructed for various mass regions, and the fit is performed for each mass region separately. In this paper, the two-dimensional templates are extended to three dimensions by additionally binning in the reconstructed $m_{\ell\ell}$. The templates are constructed by reweighting simulated DY events as analytical functions of generator-level quantities to match the differential distributions of the three pieces of the DY cross section. To reduce statistical fluctuations in the simulator, each event is used twice, once with $+c_*$ and once with $-c_*$, with a weight of 0.5 to keep the normalization unchanged.

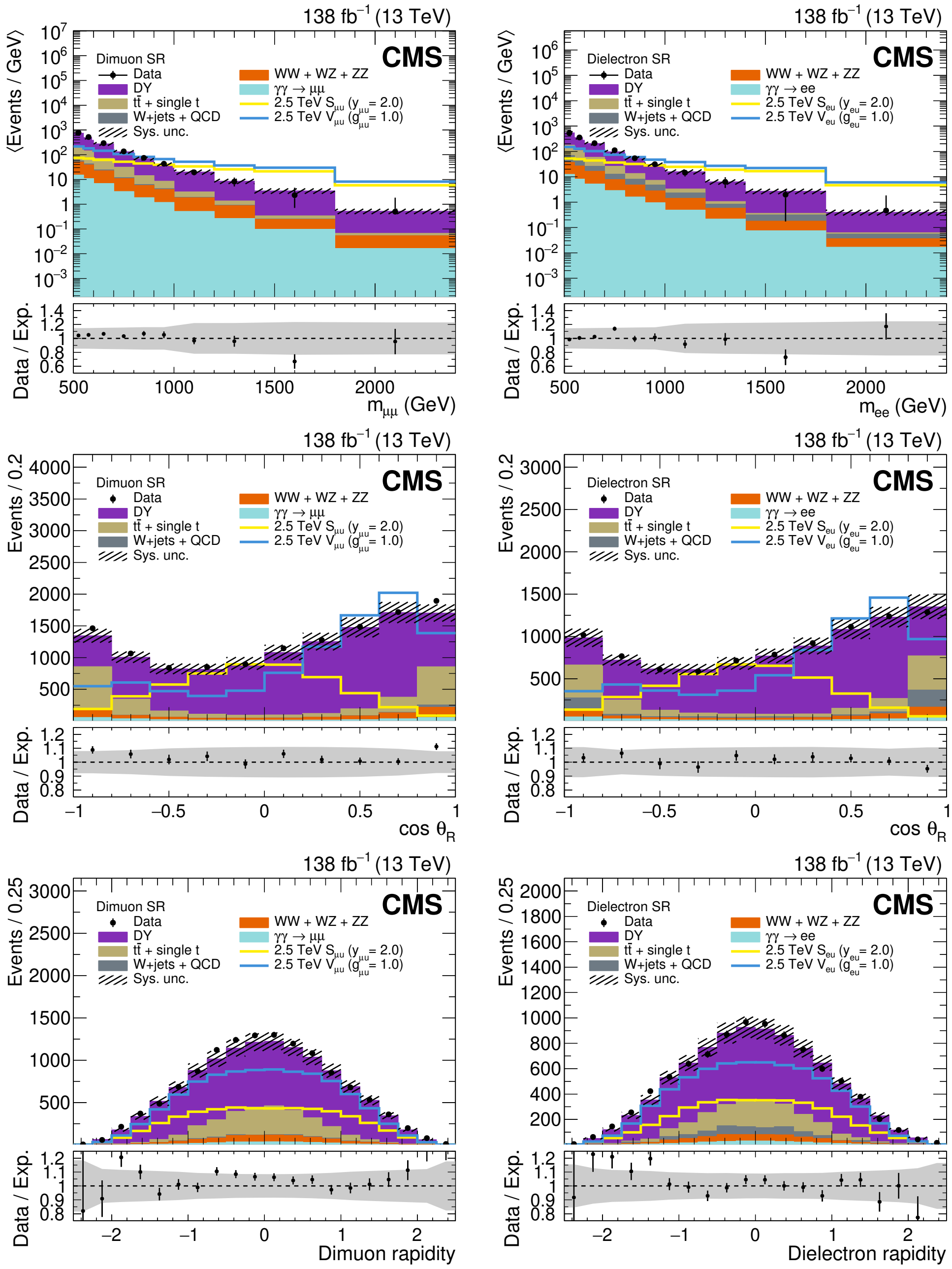

Figure 2. A comparison of data and expected background distributions in the dilepton invariant mass $m_{\ell\ell}$ (upper row), c_{R} (middle row), and dilepton rapidity (lower row). The distribution of $m_{\ell\ell}$ is shown as the average number of events per bin, whereas the distributions of c_{R} and rapidity are shown as the number of events per 0.2 in c_{R} and 0.25 in rapidity. The left (right) plots show the $\mu\mu$ (ee) channel. The blue histogram represents the signal yield of a hypothetical 2.5 TeV $\mathrm{S}_{\mu\mathrm{u}}$ (S_{eu}) with $y_{\mu\mathrm{u}}$ (y_{eu}) = 2.0, while the yellow histogram represents the signal yield of a hypothetical 2.5 TeV $\mathrm{V}_{\mu\mathrm{u}}$ (V_{eu}) with $g_{\mu\mathrm{u}}$ (g_{eu}) = 1.0. The black points with error bars represent the data and their statistical uncertainties. The background expectation is shown as stacked histograms. The hatched band shows the total systematic uncertainty in the expected background yield. The lower panels show the ratios of the data to the expectation. The gray bands represent the normalized uncertainty in the predicted yield. The error bars in the ratio plot represent the normalized statistical uncertainty in the data.

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The reweighting functions for the DY templates, f_s, f_a, and f_α respectively, are:

$$w_\mathrm{s}(|c_*|) = \frac{1+c_*^2}{1+c_*^2+\alpha\left(1-c_*^2\right)}, \tag{7.2}$$

$$w_\mathrm{a}(c_*) = \frac{c_*}{1+c_*^2+\alpha\left(1-c_*^2\right)}, \text{ and} \tag{7.3}$$

$$w_\alpha(|c_*|) = \frac{1-c_*^2}{1+c_*^2+\alpha\left(1-c_*^2\right)}. \tag{7.4}$$

The denominator of the DY reweighting functions is determined for each event from distributions of simulated SM DY events that are binned in $\cos\theta^*$ and generator-level $|y|$. The α values in the denominator are determined by fitting the generator-level distributions of the simulated events. Finally, to avoid negative values in the antisymmetric template, f_a, a linear combination of f_s and f_a is used in the fit, defined by $f_\pm = \frac{f_\mathrm{s}\pm f_\mathrm{a}}{2}$.

For the templates corresponding to the two LQ terms, $f_{\mathrm{LQ(pure)}}$ and $f_{\mathrm{LQ(int)}}$, events are reweighted as functions of both c_* and $m_{\ell\ell}$. The reweighting functions are given by:

$$w^{S,V}_{\mathrm{LQ(pure)}}(c_*, m_{\ell\ell}) = \left(N^{S,V}_{\mathrm{pure}}(m_{\ell\ell}) \frac{(1\mp c_*)^2}{\left(1-c_*+\frac{2m_{\mathrm{LQ}}^2}{m_{\ell\ell}^2}\right)^2} \right) \frac{1}{N_{\mathrm{SM}}(m_{\ell\ell})(1+c_*^2)} \tag{7.5}$$

and

$$w^{S,V}_{\mathrm{LQ(int)}}(c_*, m_{\ell\ell}) = \left(N^{S,V}_{\mathrm{int}}(m_{\ell\ell}) \frac{(1\mp c_*)^2}{\left(1-c_*+\frac{2m_{\mathrm{LQ}}^2}{m_{\ell\ell}^2}\right)} \right) \frac{1}{N_{\mathrm{SM}}(m_{\ell\ell})(1+c_*^2)}, \tag{7.6}$$

where S and V denote the scalar or vector case. The prefactors, $N^{S,V}_{\mathrm{pure/int}}(m_{\ell\ell})$, depend on the vector and axial-vector couplings of the quarks and leptons to the Z boson, as well as the quark charges. Thus, templates for an LQ coupled to a lepton and quark of specific flavors have different shapes compared to an LQ coupled to a different lepton and quark. The $N_{\mathrm{SM}}(m_{\ell\ell})$ prefactor represents the coefficient of the symmetric term $(1+c_*^2)$ in the SM DY angular distribution. The denominators of the LQ reweighting functions are different from those of the SM DY functions, calculated from the analytical form of the LO SM DY cross section for each event. This is because the LQ modifies the $m_{\ell\ell}$ distribution, which must be taken into account in the reweighting.

The reweighting procedure described above has several benefits. The effects of misassigning the direction of the incident quark in the c_* computation, called the "dilution" effect, are accounted for correctly. Additionally, no dedicated MC samples need to be produced for the LQ process or its interference. The distribution of LQ events can be obtained by reweighting SM DY MC events using the analytical functional form of the LQ differential cross section.

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The reweighting procedure was further validated by fitting LQ and DY templates at the generator level to simulated LQ signals using MadGraph5_aMC@NLO using the SLQrules package [70]. Signals were generated at various mass points from 1–5 TeV. The fitted results agreed with the expected coupling values up to a maximum of 30% at $m_{\mathrm{LQ}} = 1\,\mathrm{TeV}$, decreasing with m_{LQ}. The discrepancy is attributable in part to the fact that the reweighting procedure does not account for NLO effects in the LQ exchange. We account for this in our fits by applying a 30% systematic uncertainty in the normalization of the LQ templates.

The total template for the scalar LQ case, binned in reconstructed $m_{\ell\ell}$, y, and c_{R}, is given by:

$$\begin{aligned} f_{\mathrm{data}} = \sum_j f^j_{\mathrm{bkg}} + N(\alpha)\left(\alpha\, f_\alpha + \left(1+\frac{3A_4}{8N}\right) f_+ + \left(1-\frac{3A_4}{8N}\right) f_-\right) \\ + y^4_{\mathrm{LQ}} f_{\mathrm{LQ(pure)}} + y^2_{\mathrm{LQ}} f_{\mathrm{LQ(int)}}, \end{aligned} \tag{7.7}$$

where f^j_{bkg} are templates for the non-DY backgrounds and $N(\alpha) = \frac{3}{4(2+\alpha)}$. The same template is used for the vector LQ case using the corresponding reweighting functions, and replacing y_{LQ} with g_{LQ}. The coefficients A_4, α, and either y^2_{LQ} or g^2_{LQ} are extracted in the fits to data.

Events are divided into bins based on $m_{\ell\ell}$, $|y|$, and c_{R}. For $m_{\ell\ell}$, three bins are used with bin edges at 500, 700, and 1000 GeV, with the third bin containing all events with $m_{\ell\ell} > 1000\,\mathrm{GeV}$. Three bins are defined for $|y|$, with edges at 0, 0.6, 1, and 2.4. The binning in c_{R} depends on the rapidity. Within the first rapidity bin, events are divided into eight bins in c_{R} of width 0.25. For the other two rapidity bins, events are divided into six bins in c_{R}, with edges of −1, −0.5, −0.25, 0, 0.25, 0.5, and 1. Bin edges were chosen after ensuring that there were sufficient simulated events in each bin, and fit uncertainties were minimized without losing precision.

Additional templates are created for the other background processes, with one template each for the MisID background, photon-induced dilepton production, DY $\tau\tau$ production, the combined top quark backgrounds ($\mathrm{t\bar{t}}$, tW), and the combined diboson backgrounds (WW, ZZ, WZ). The top quark and MisID templates are symmetrized in c_{R} to reduce statistical fluctuations. The diboson, photon-induced dilepton, and DY $\tau\tau$ backgrounds are not symmetrized because of their significant inherent asymmetry.

8 Systematic uncertainties

Systematic uncertainties in the normalization and shapes of the templates arise from a variety of sources, and are incorporated in the fit to data through nuisance parameters in the likelihood. Systematic uncertainties affecting template normalizations are included using log-normal priors. For systematic uncertainties that change the shape of a template, shifted templates are constructed by varying the source of the systematic uncertainty up and down within its uncertainty. The uncertainties are incorporated into the likelihood by interpolation between the nominal and shifted templates, constrained with a Gaussian prior. Table 2 shows the impact of each uncertainty in the fitted LQ coupling for representative scalar and vector signal hypotheses.

A significant source of uncertainty is due to the creation of the LQ signal templates using LO reweighting of NLO DY MC events. A normalization uncertainty of 30% in the

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Source	Relative contribution (%)							
	y^2_{eu}	y^2_{ed}	$y^2_{\mu\mathrm{u}}$	$y^2_{\mu\mathrm{d}}$	g^2_{eu}	g^2_{ed}	$g^2_{\mu\mathrm{u}}$	$g^2_{\mu\mathrm{d}}$
Statistical uncertainty	84	84	81	79	34	33	25	32
LQ LO reweighting	21	31	27	25	28	27	53	37
MC and MisID backgrounds statistical uncertainty	15	15	14	16	35	56	31	46
α_S + renormalization/factorization scales	7	11	20	22	15	19	28	32
eμ shape corrections	7	8	17	16	11	4	16	11
Background cross sections	12	14	33	36	23	22	54	48
Integrated luminosity	13	13	20	23	19	19	32	38
Pileup	6.9	6.4	9.5	8.8	5.1	5.7	5.1	6.0
PDFs	6.0	6.9	7.1	8.2	8.8	4.6	11	8.8
Trigger efficiency	11	9.0	2.5	1.3	19	7.1	4.3	6.3
Lepton momentum scale	17	22	5.7	3.1	30	12	14	6.9
Lepton identification/isolation	33	20	9.9	10	62	57	12	16
MisID shape & normalization	17	19	15	16	38	58	31	47

Table 2. The contributions of the statistical uncertainty and of individual sources of systematic uncertainty to the total variance in the fitted value of y^2_{LQ} (g^2_{LQ}) for a scalar (vector) m_{LQ} of 2.5 TeV. For a given source of uncertainty, the impact is determined by fixing its associated nuisance parameter to the postfit value and evaluating the change in the total uncertainty. The quadrature sum of the uncertainties is approximately equal to the total uncertainty in y^2_{LQ} (g^2_{LQ}) for a scalar (vector) m_{LQ} of 2.5 TeV.

coupling is assigned to the pure and interference LQ templates. This uncertainty is based on bias tests performed on simulations with injected signal events that were generated with MadGraph5_aMC@NLO following ref. [70]. This uncertainty does not affect the shape of the templates.

Several sources of systematic uncertainty are due to the modeling of leptons in simulation. These include uncertainties in the momentum scale, the efficiency of the reconstruction and identification criteria, and the trigger efficiency. These uncertainties are small for the muon channel, but are dominant in the electron channel.

Additional systematic uncertainties are applied to templates estimated from simulation. The uncertainty in the PDFs is assigned from the Hessian variations of the PDF sets. Uncertainties due to missing higher-order contributions are estimated by varying the renormalization and factorization scales independently by factors of two. Additional uncertainties are assigned to the cross sections of the DY, $\mathrm{t\bar{t}}$, and diboson processes based on comparisons between generators, of size 3, 5, and 4%, respectively. Similarly, an uncertainty of 6% is assigned to the normalization of the $\gamma\gamma \to \ell\ell$ process, based on a comparison between the Suri-Yennie structure functions and the LuxQED photon PDFs [77, 78]. The statistical uncertainties due to the limited number of MC events are implemented using the simplified Barlow-Beeston approach [79]. Since the bin contents of $\pm c_*$ are correlated because each event is used twice, each pair of $\pm c_*$ bins is varied together and accounts for a separate nuisance parameter.

The MisID background is assigned a normalization uncertainty of 50% based on closure studies of the misidentification rate in simulation and a shape uncertainty based on the difference between the MisID estimate in SS and OS events. The MisID uncertainty primarily affects the electron channel, given the higher rate of misidentified electrons than muons.

The $\mathrm{t\bar{t}}$ and diboson templates are assigned a shape uncertainty due to the correction to the c_{R} distributions derived from $\mathrm{e\mu}$ events. The integrated luminosities for the 2016, 2017, and 2018 data-taking years have 1.2–2.5% individual uncertainties [80–82], while the overall uncertainty for the 2016–2018 period is 1.6%. Small uncertainties in the modeling of pileup are also incorporated.

The uncertainties in the PDFs, pileup, electron and muon efficiencies, MC cross sections, luminosity, and the LQ template normalization are correlated for all the three data-taking years. The $\mathrm{e\mu}$ shape corrections, and renormalization and factorization scale corrections are correlated for the 2017 and 2018 periods. The rest are treated independently per year. In the results for the scalar LQ couplings, the contribution of statistical uncertainties is larger than the systematic uncertainties. However for the vector LQ couplings, the systematic uncertainties have a larger contribution. This is because of the differences in shapes between the scalar and vector LQ templates.

Table 2 shows that the largest contributors to the uncertainties in $y^2_{\mathrm{\mu u}}$, $y^2_{\mathrm{\mu d}}$, $g^2_{\mathrm{\mu u}}$, and $g^2_{\mathrm{\mu d}}$ are those arising from the LO reweighting scheme, the renormalization and factorization scales, and the background cross sections. Additionally, the electron identification and isolation has major contributions to the uncertainties in y^2_{eu}, y^2_{ed}, g^2_{eu}, and g^2_{ed}. The post-fit up and down variations of these systematic uncertainties are asymmetric in their impacts on the LQ couplings. This is because the likelihood function for each model is asymmetric in y^2_{LQ} (g^2_{LQ}), and not quadratic. The shapes of the likelihoods follow from eqs. (2.3) and (2.4). For each LQ model considered, the prefactor $N^{S(V)}_{\mathrm{int}}$ can assume positive or negative values based on the fermions involved in the LQ exchange, leading to constructive or destructive interference. Accordingly, combinations of the pure LQ exchange term and the LQ-SM interference term result in asymmetric likelihoods, that become highly nonquadratic for large couplings.

9 Results

Template fits are performed to the data for each LQ signal hypothesis, following eq. (7.7). The COMBINE package [83] is used to perform maximum likelihood fits to the data. A range of positive and negative values of y^2_{LQ} (g^2_{LQ}) is floated in the fit in order to ensure fit stability. The extracted best fit parameters for a candidate m_{LQ} of 2.5 TeV are shown in tables 3 and 4. The corresponding upper and lower bounds of the Feldman-Cousins intervals [84] for y^2_{LQ} (g^2_{LQ}) are reported as well. In the SM, the expected value of A_0 is 0.05, and that of A_4 is 1.61. These quantities were measured more precisely in ref. [36]. The best fit values for g^2_{ed} and $g^2_{\mathrm{\mu d}}$ are positive, while the others are negative. This is due to the destructive interference between LQ and SM amplitudes for $\mathrm{V_{ed}}$ and $\mathrm{V_{\mu d}}$ exchanges, and constructive interference in the other models. All results are found to be consistent with the SM background expectations. The fit results are shown in figures 3–6. In each figure, the overall signal yield is scaled by -10 because the sum of the pure and interference contributions scaled by the post-fit values of y^4_{LQ} (g^4_{LQ}) and y^2_{LQ} (g^2_{LQ}) is negative.

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Model	A_0	A_4	y^2_{LQ}	Lower bound on y^2_{LQ}	Upper bound on y^2_{LQ}
$\mathrm{S}_{\mu u}$	0.02 ± 0.06	1.59 ± 0.07	$-0.13^{+0.14}_{-0.15}$ (stat)$^{+0.06}_{-0.11}$ (syst)	0	0.082
$\mathrm{S}_{\mu d}$	0.02 ± 0.06	1.60 ± 0.07	$-0.11^{+0.18}_{-0.20}$ (stat)$^{+0.09}_{-0.13}$ (syst)	0	0.119
S_{eu}	0.07 ± 0.07	1.61 ± 0.08	$-0.10^{+0.15}_{-0.17}$ (stat)$^{+0.07}_{-0.11}$ (syst)	0	0.093
S_{ed}	0.07 ± 0.07	1.62 ± 0.08	$-0.09^{+0.20}_{-0.23}$ (stat)$^{+0.11}_{-0.13}$ (syst)	0	0.138

Table 3. Best fit values of A_0, A_4, and y^2_{LQ} for scalar LQ models. The Feldman-Cousins confidence interval for y^2_{LQ} is shown at 68% CL. Results are shown for a candidate m_{LQ} of 2.5 TeV.

Limits at 95% CL are set on the absolute value of the LQ-fermion couplings as a function of the m_{LQ} for each coupling and spin hypothesis. The limit-setting procedure employs a modified frequentist approach based on the $\mathrm{CL_s}$ criterion [85, 86], using an asymptotic approximation for the distribution of the test statistic [87]. Limits extracted with this approach are nearly identical to those obtained from the Feldman-Cousins method. The limits are shown in figures 7 and 8 for the scalar case, and figures 9 and 10 for the vector case, assuming branching fractions of 100% for each channel.

In general, for equal coupling values, the cross sections for vector LQ production are larger than for scalar LQ production, hence the limits on $|g_{\mathrm{LQ}}|$ are generally stronger than those on $|y_{\mathrm{LQ}}|$. The limits on up-type couplings are stronger than the limits on down-type couplings because of the larger up quark content of the proton. In the V_{ed} and $\mathrm{V}_{\mu d}$ cases, the interference process is negative, and the likelihood functions for these models are thus quite asymmetric and nonquadratic. This leads to smaller cross sections and weaker expected and observed limits than the other cases. The uncertainties in the expected limits are also accordingly larger than in the other cases. Further, the observed limit on $|g_{ed}|$ is more stringent than the expected limit, despite the positive best fit value for the V_{ed} mass of 2.5 TeV, as shown in table 4. This stems from the asymmetric nuisance impacts arising from the nonquadraticity in the likelihood, as discussed in section 8.

At $m_{\mathrm{LQ}} \gg m_{\ell\ell}$, the cross section scales as $y^2_{\mathrm{LQ}}/m^2_{\mathrm{LQ}}$ ($g^2_{\mathrm{LQ}}/m^2_{\mathrm{LQ}}$), leading to the linearly increasing limits that are observed. Coupling values larger than 4π are nonperturbative.

For the scalar case, coupling values of 0.4–1.1 (0.3–1.0) are excluded for LQs coupled to electrons (muons) with masses between 1–5 TeV. These limits significantly extend the previous best limits from single production [24], which excluded S_{eu} and S_{ed} masses up to 1.7 TeV depending on the coupling, and pair production [25], which excluded S_{eu} and S_{ed} masses up to 1.4 TeV independent of the mass. Similarly, for the vector case, coupling values of 0.2–0.5 (0.1–0.4) are excluded for LQs coupled to electrons (muons). These are the first limits on vector LQs coupled to first- and second-generation fermions obtained via nonresonant t-channel exchange, extending the sensitivity of previous searches.

10 Summary

A search for the t-channel exchange of leptoquarks (LQs) coupled to first- and second-generation fermions has been presented. The search uses proton-proton collision data at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 138 fb^{-1}. Both scalar and vector

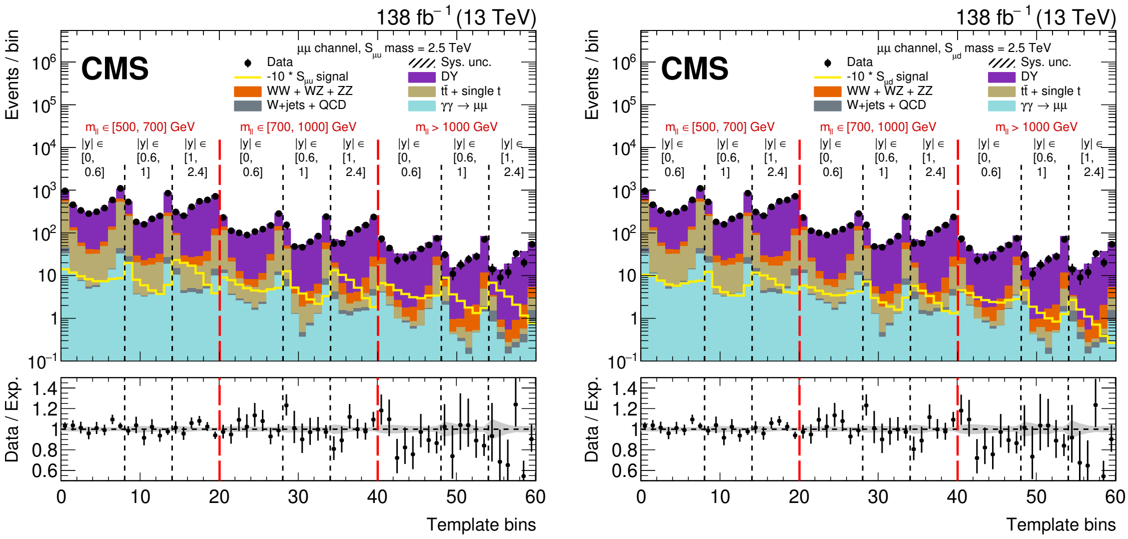

Figure 3. The observed data in the dimuon channel and the fitted signal-plus-background templates, shown for the $S_{\mu u}$ (left) and $S_{\mu d}$ (right) scenarios with a candidate m_{LQ} of 2.5 TeV. The black points are the observed data, the stacked histograms represent the backgrounds, and the yellow histogram shows the fitted LQ signal scaled by −10. Distributions of events are binned in the reconstructed $m_{\ell\ell}$ (vertical red dashed lines), $|y|$ (vertical black dashed lines), and c_R (section 7). The lower panels show the ratios of the data to the expectation. The gray bands represent the normalized uncertainty in the predicted yield. The error bars in the ratio plot represent the normalized statistical uncertainty in the data.

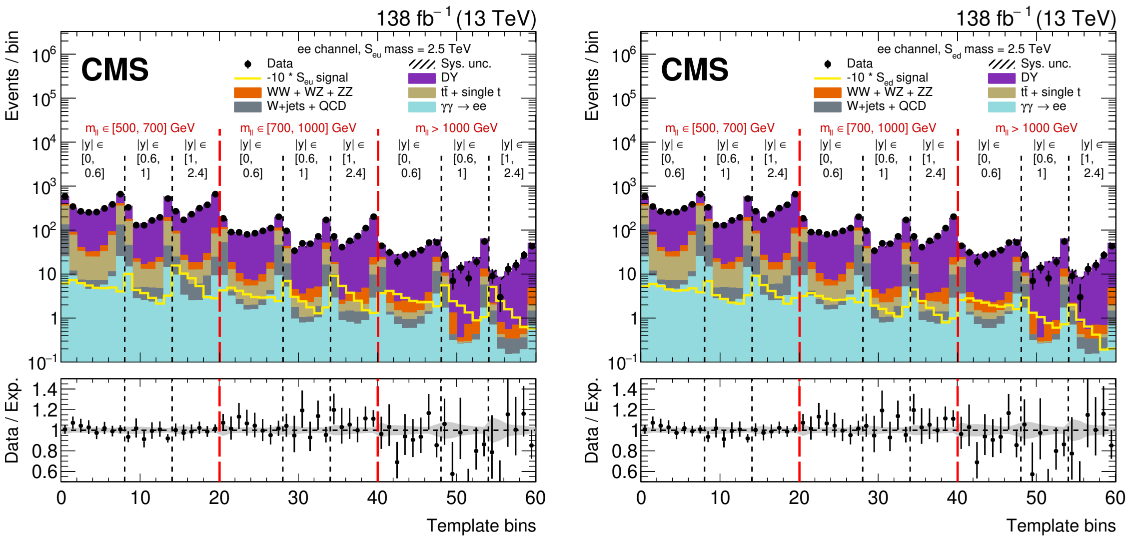

Figure 4. The observed data in the dielectron channel and the fitted signal-plus-background templates, shown for the S_{eu} (left) and S_{ed} (right) scenarios with a candidate m_{LQ} of 2.5 TeV. The black points are the observed data, the stacked histograms represent the backgrounds, and the yellow histogram shows the fitted LQ signal scaled by −10. Distributions of events are binned in the reconstructed $m_{\ell\ell}$ (vertical red dashed lines), $|y|$ (vertical black dashed lines), and c_R (section 7). The lower panels show the ratios of the data to the expectation. The gray bands represent the normalized uncertainty in the predicted yield. The error bars in the ratio plot represent the normalized statistical uncertainty in the data.

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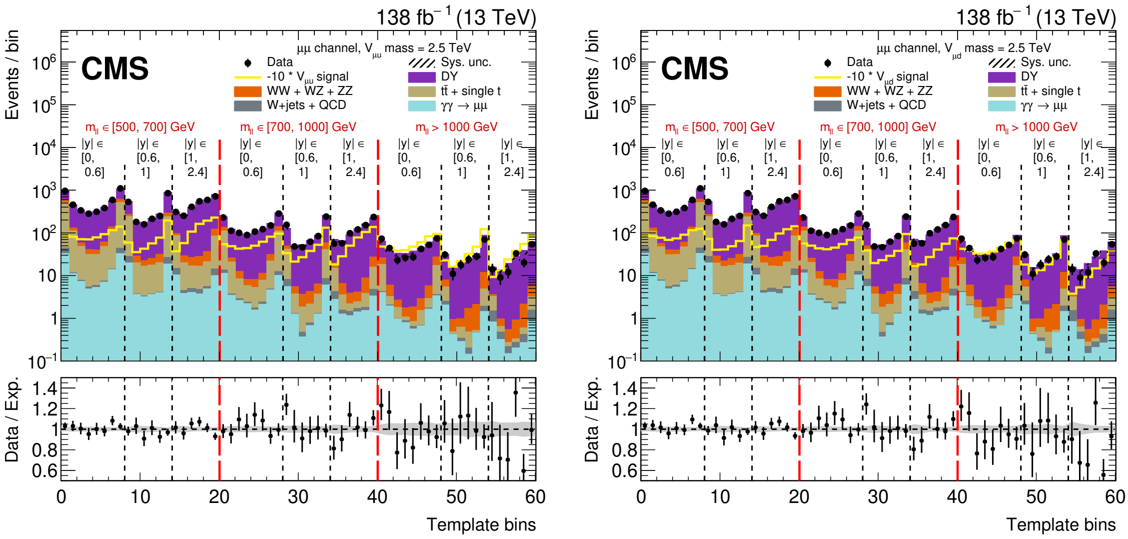

Figure 5. The observed data in the dimuon channel and the fitted signal-plus-background templates, shown for the $V_{\mu u}$ (left) and $V_{\mu d}$ (right) scenario with a candidate m_{LQ} of 2.5 TeV. The black points are the observed data, the stacked histograms represent the backgrounds, and the yellow histogram shows the fitted LQ signal scaled by −10. Distributions of events are binned in the reconstructed $m_{\ell\ell}$ (vertical red dashed lines), $|y|$ (vertical black dashed lines), and c_R (section 7). The lower panels show the ratios of the data to the expectation. The gray bands represent the normalized uncertainty in the predicted yield. The error bars in the ratio plot represent the normalized statistical uncertainty in the data.

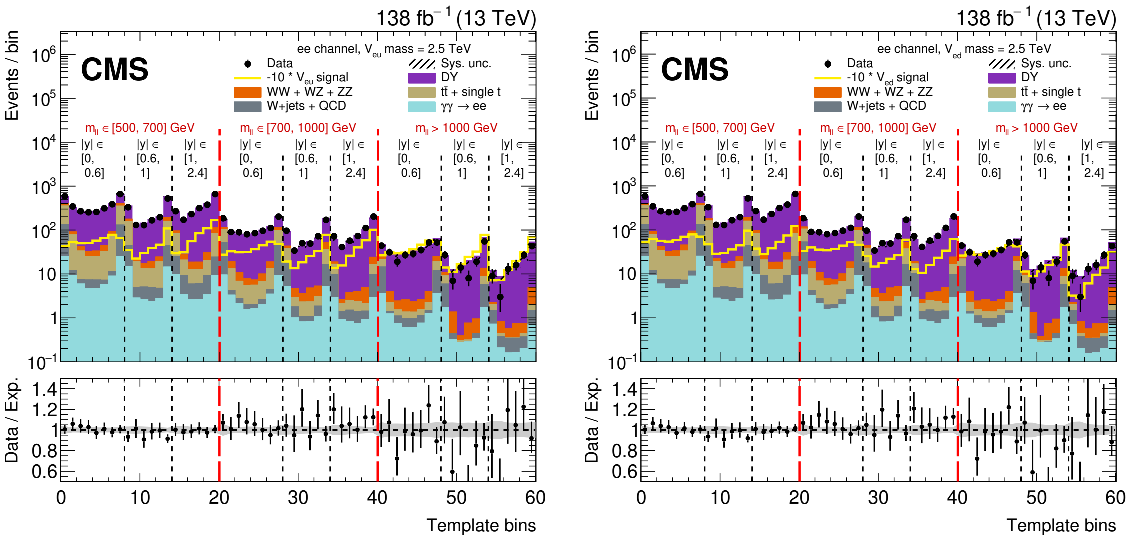

Figure 6. The observed data in the dielectron channel and the fitted signal-plus-background templates, shown for the V_{eu} (left) and V_{ed} (right) scenario with a candidate m_{LQ} of 2.5 TeV. The black points are the observed data, the stacked histograms represent the backgrounds, and the yellow histogram shows the fitted LQ signal scaled by −10. Distributions of events are binned in the reconstructed $m_{\ell\ell}$ (vertical red dashed lines), $|y|$ (vertical black dashed lines), and c_R (section 7). The lower panels show the ratios of the data to the expectation. The gray bands represent the normalized uncertainty in the predicted yield. The error bars in the ratio plot represent the normalized statistical uncertainty in the data.

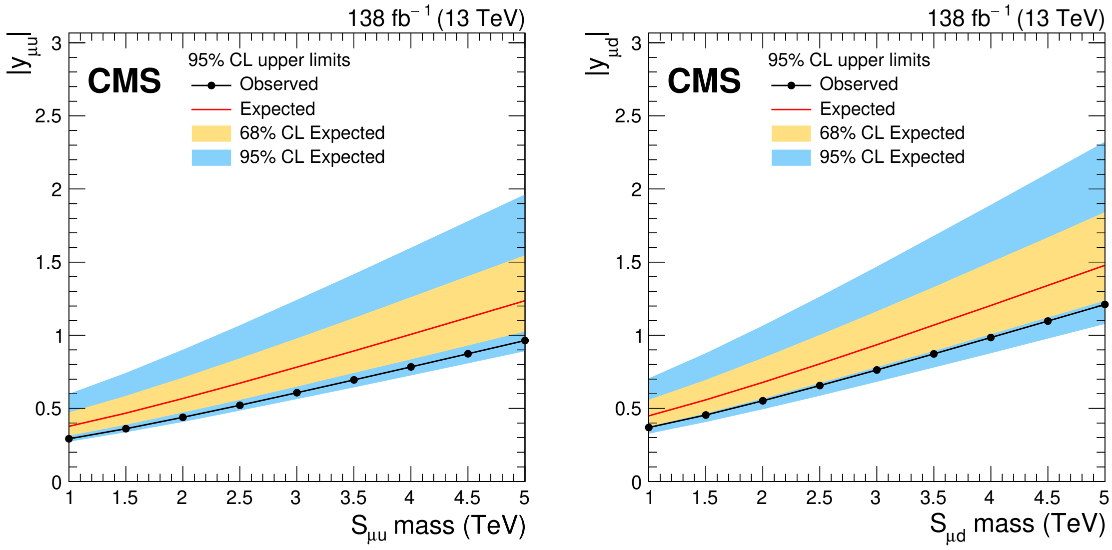

Figure 7. Upper limits at 95% CL on the LQ-fermion couplings, $|y_{\mathrm{\mu u}}|$ (left) and $|y_{\mathrm{\mu d}}|$ (right), as a function of m_{LQ} for scalar LQs coupled to muons. The black points show the observed limits, the red line shows the expected limits, and the yellow and blue bands show the variations on the expected limit at 68% and 95% CL, respectively.

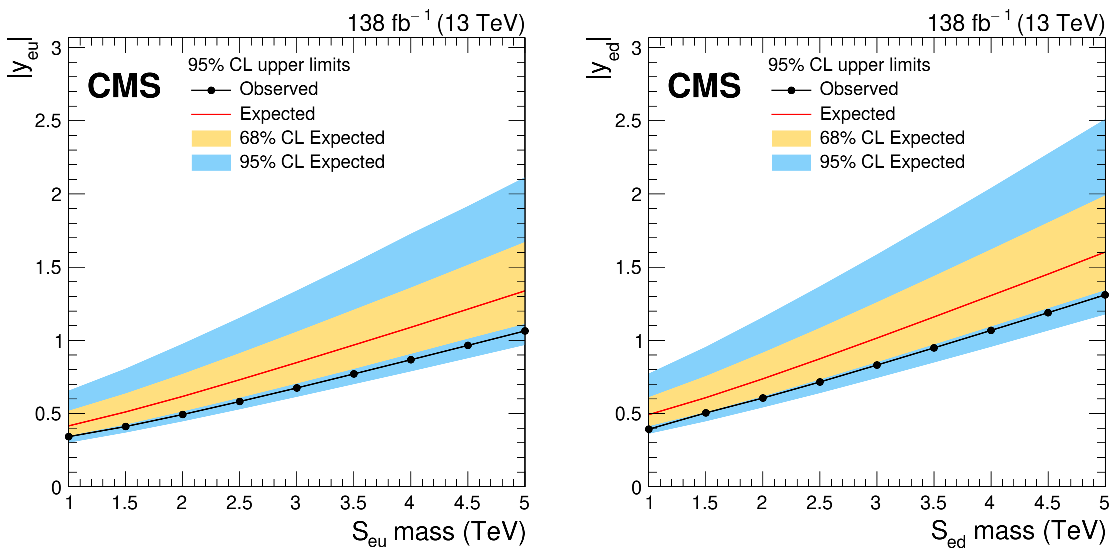

Figure 8. Upper limits at 95% CL on the LQ-fermion couplings, $|y_{\mathrm{eu}}|$ (left) and $|y_{\mathrm{ed}}|$ (right), as a function of m_{LQ} for scalar LQs coupled to electrons. The black points show the observed limits, the red line shows the expected limits, and the yellow and blue bands show the variations on the expected limit at 68% and 95% CL, respectively.

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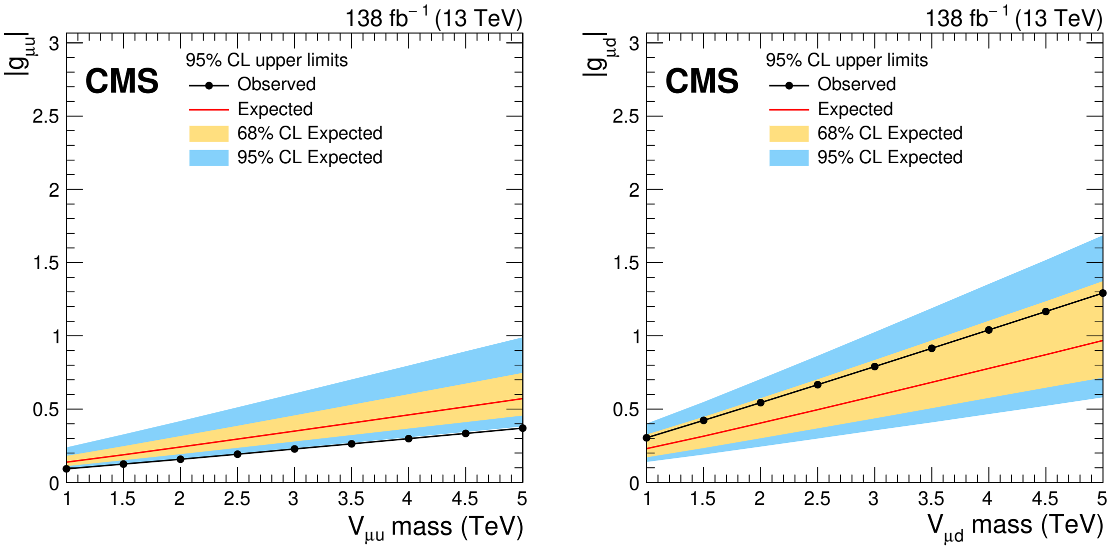

Figure 9. Upper limits at 95% CL on the LQ-fermion couplings, $|g_{\mu u}|$ (left) and $|g_{\mu d}|$ (right), as a function of m_{LQ} for vector LQs coupled to muons. The black points show the observed limits, the red line shows the expected limits, and the yellow and blue bands show the variations on the expected limit at 68% and 95% CL, respectively.

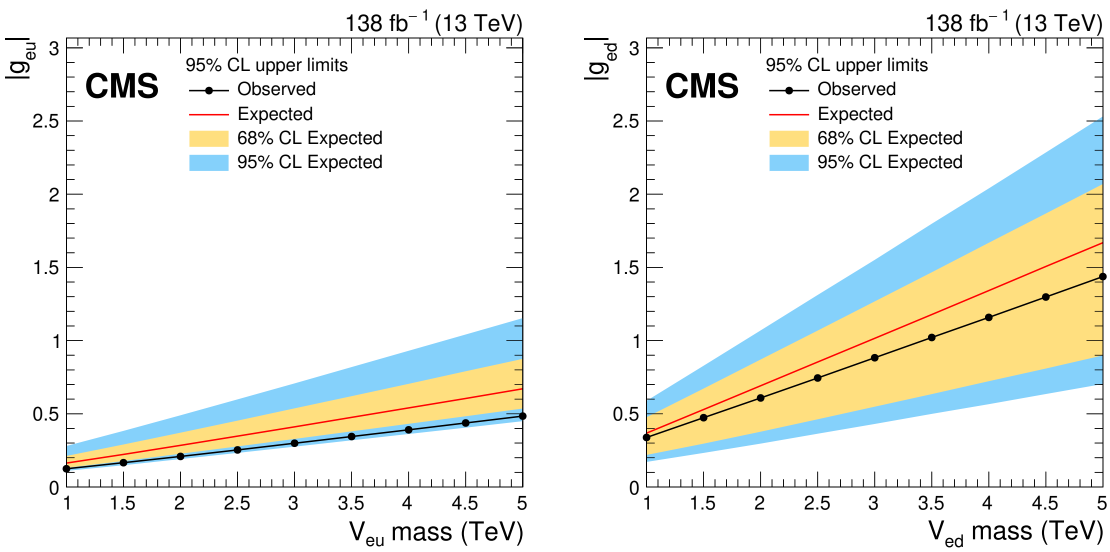

Figure 10. Upper limits at 95% CL on the LQ-fermion couplings, $|g_{eu}|$ (left) and $|g_{ed}|$ (right), as a function of m_{LQ} for vector LQs coupled to electrons. The black points show the observed limits, the red line shows the expected limits, and the yellow and blue bands show the variations on the expected limit at 68% and 95% CL, respectively.

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Model	A_0	A_4	g^2_{LQ}	Lower bound on g^2_{LQ}	Upper bound on g^2_{LQ}
$\mathrm{V}_{\mu\mathrm{u}}$	0.01 ± 0.05	1.63 ± 0.06	$-0.10^{+0.02}_{-0.02}$ (stat)$^{+0.04}_{-0.08}$ (syst)	0	0.029
$\mathrm{V}_{\mu\mathrm{d}}$	0.01 ± 0.05	1.61 ± 0.06	$0.14^{+0.05}_{-0.05}$ (stat)$^{+0.14}_{-0.07}$ (syst)	0.036	0.328
V_{eu}	0.05 ± 0.07	1.66 ± 0.08	$-0.09^{+0.03}_{-0.03}$ (stat)$^{+0.04}_{-0.08}$ (syst)	0	0.026
V_{ed}	0.06 ± 0.07	1.64 ± 0.08	$0.13^{+0.06}_{-0.06}$ (stat)$^{+0.17}_{-0.09}$ (syst)	0.038	0.352

Table 4. Best fit values of A_0, A_4, and g^2_{LQ} for vector LQ models. The Feldman-Cousins confidence interval for g^2_{LQ} is shown at 68% CL. Results are shown for a candidate m_{LQ} of 2.5 TeV.

LQs are considered, with masses between 1 and 5 TeV, for exclusive LQ couplings to an up or a down quark and a muon or an electron. The *t*-channel exchange of an LQ modifies the dilepton angular distributions at masses well below the resonance mass of the LQ. A template fit to the angular and invariant mass distributions of high-mass dilepton events is used to distinguish the signal process from the dominant Drell-Yan background, incorporating the interference effects. No evidence for such LQs is observed. Limits are set at 95% confidence level on the LQ-fermion couplings. For scalar LQs with masses in the 1–5 TeV range, coupling values greater than 0.4–1.3 (0.3–1.0) are excluded for LQs coupled to a muon or an electron, and an up (down) quark, and couplings greater than 0.3–1.4 (0.1–0.5) are excluded for the respective vector LQs. This search is sensitive to LQs with significantly higher masses than prior single- and pair-production searches, establishing stringent limits on LQs with masses up to 5 TeV.

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