

## 93. Leptoquarks

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Leptoquarks (LQs) are hypothetical particles carrying both baryon number (B) and lepton number (L). The possible quantum numbers of LQ states can be constrained by assuming that their direct interactions with the ordinary Standard Model (SM) fermions are dimensionless and invariant under the SM gauge group. Table 93.1 lists all possible quantum numbers under this assumption [1]. The columns labeled  $SU(3)_C$ ,  $SU(2)_W$ , and  $U(1)_Y$  in Table 93.1 indicate the QCD representation, the weak isospin representation, and the weak hypercharge, respectively. The spin of a LQ state is taken to be either 1 (vector LQ) or 0 (scalar LQ). If we do not require LQ states to couple directly with SM fermions, quantum number assignments beyond those listed in Table 93.1 become possible [2,3].

**Table 93.1:** Possible leptoquarks (LQs) and their quantum numbers.

Spin	$3B + L$	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	Allowed coupling
0	-2	$\bar{3}$	1	1/3	$\bar{q}_L^c \ell_L$ or $\bar{u}_R^c e_R$
0	-2	$\bar{3}$	1	4/3	$\bar{d}_R^c e_R$
0	-2	$\bar{3}$	3	1/3	$\bar{q}_L^c \ell_L$
1	-2	$\bar{3}$	2	5/6	$\bar{q}_L^c \gamma^\mu e_R$ or $\bar{d}_R^c \gamma^\mu \ell_L$
1	-2	$\bar{3}$	2	-1/6	$\bar{u}_R^c \gamma^\mu \ell_L$
0	0	3	2	7/6	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$
0	0	3	2	1/6	$\bar{d}_R \ell_L$
1	0	3	1	2/3	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$
1	0	3	1	5/3	$\bar{u}_R \gamma^\mu e_R$
1	0	3	3	2/3	$\bar{q}_L \gamma^\mu \ell_L$

LQ states are predicted in various extensions of the SM. The Pati-Salam model [4] is one such example. LQs also appear in grand unified theories based on  $SU(5)$  [5],  $SO(10)$  [6] which includes Pati-Salam color  $SU(4)$ , and larger gauge groups. The presence of LQs at TeV-scale affect the renormalization group of the standard model gauge coupling strengths and may enable gauge coupling unification required by the grand unified theories [7]. Scalar quarks in supersymmetric models with  $R$ -parity violation may also exhibit LQ-like Yukawa couplings. Consequently, bounds on LQ states can constrain  $R$ -parity-violating supersymmetric models [8,9]. LQs are expected to exist at the TeV-scale in extended technicolor models [10,11] where they appear as bound states of techni-fermions. Models involving quark and lepton compositeness also predict light LQ states [12]. LQ-induced two-quark two-lepton interactions often lead to lepton-flavor non-universalities in heavy quark decays. The so called  $R(D)$ ,  $R(D^*)$  anomaly observed in the semi-leptonic  $B$  decays [13] may be explained by models with TeV-scale LQs.

Bounds on LQ states are obtained both directly and indirectly. Direct limits arise from production cross sections at colliders, while indirect limits are derived from constraints on LQ-induced two-quark two-lepton interactions. The quantum number assignments in Table 93.1 allow several LQ states to couple to both left- and right-handed quarks simultaneously. Such LQ states are termed non-chiral and give rise to low-energy interactions of the form:

$$(\bar{u}_R q_{Li})(\bar{e}_R \ell_{Lj})\epsilon^{ij} \qquad (\bar{d}_R q_{Li})(\bar{\ell}_L^i e_R). \qquad (93.1)$$

Here  $q_L$  and  $\ell_L$  denote the left-handed quark and lepton  $SU(2)_W$  doublets, while  $u_R$ ,  $d_R$  and  $e_R$  are the right-handed up-type quark, down-type quark and charged lepton  $SU(2)_W$  singlets. Indices  $i$  and  $j$  correspond to weak isospin, and  $\epsilon^{ij}$  is the anti-symmetric Levi-Civita tensor of  $SU(2)_W$ . These interactions affect the ratio  $\Gamma(\pi \rightarrow e\nu)/\Gamma(\pi \rightarrow \mu\nu)$  [14]. Non-chiral scalar LQs also contribute to the anomalous magnetic moments of charged leptons [15, 16]. On the other hand, chiral LQ exchanges induce effective two-quark two-lepton interactions below the LQ mass scale:

$$\begin{aligned}
& (\bar{q}_L^i \gamma^\mu q_{Li})(\bar{\ell}_L^j \gamma_\mu \ell_{Lj}), & (\bar{q}_L^i \gamma^\mu q_{Li})(\bar{e}_R \gamma_\mu e_R), & (\bar{q}_L^i \gamma^\mu (\vec{\sigma})_i^j q_{Lj}) \cdot (\bar{\ell}_L^k \gamma_\mu (\vec{\sigma})_k^l \ell_{Li}), \\
& (\bar{u}_R \gamma^\mu u_R)(\bar{\ell}_L^j \gamma_\mu \ell_{Lj}), & (\bar{u}_R \gamma^\mu u_R)(\bar{e}_R \gamma_\mu e_R), & \\
& (\bar{d}_R \gamma^\mu d_R)(\bar{\ell}_L^j \gamma_\mu \ell_{Lj}), & (\bar{d}_R \gamma^\mu d_R)(\bar{e}_R \gamma_\mu e_R). & 
\end{aligned} \tag{93.2}$$

Here  $(\vec{\sigma})_i^j$  denotes the Pauli matrices of  $SU(2)_W$ . Generation labels for quarks and leptons are suppressed in (93.1) and (93.2). If a LQ couples to quarks and leptons from multiple generations in the mass eigenbasis, it can induce flavor-changing neutral currents and lepton-family-number violations. Indirect limits provide stringent constraints on non-chiral or flavor-violating LQs. Therefore, collider searches often assume that a LQ state couples only to a single generation of quarks and leptons in a chiral interaction, for which indirect limits are weaker. LQs that couple exclusively to the first, second, and third generation are referred to as first-, second-, and third-generation LQs, respectively. It is also possible to consider LQ states which couple dominantly with the  $i$ -th generation quarks and the  $j$ -th generation leptons ( $i \neq j$ ) without conflicting with indirect constraints. Such couplings have recently gained renewed attention. See Ref. [17, 18] and [19], and references therein for collider search strategies and limits on the pair-production cross sections of this class of LQ states.

Limits on the LQ induced two-quark two-lepton interactions can be derived from low-energy experiments and from collider experiments below threshold. Refs. [20–22] give extensive lists of such limits. For the isoscalar scalar and vector LQs,  $S_0$  and  $V_0$ , for example, which couple with the first- (second-) generation left-handed quark, and the first-generation left-handed lepton, the bounds  $\lambda^2 < 0.07 \times (M_{LQ}/1 \text{ TeV})^2$  for  $S_0$ , and  $\lambda^2 < 0.4 \times (M_{LQ}/1 \text{ TeV})^2$  for  $V_0$  ( $\lambda^2 < 0.7 \times (M_{LQ}/1 \text{ TeV})^2$  for  $S_0$ , and  $\lambda^2 < 0.5 \times (M_{LQ}/1 \text{ TeV})^2$  for  $V_0$ ) can be derived from the limits listed in Ref. [22]. Here  $\lambda$  and  $M_{LQ}$  denote the LQ coupling strength and the LQ mass, respectively. See also Refs. [23, 24] for earlier studies. The  $e^+e^-$  collider experiments are sensitive to the indirect effects coming from  $t$ - and  $u$ -channel exchanges of LQs in the  $e^+e^- \rightarrow q\bar{q}$  process. The HERA experiments give bounds on the LQ-induced two-quark two-lepton interaction. It should also be stressed that the measurements of the high-mass Drell-Yan (DY) cross sections,  $pp \rightarrow \ell\nu$  and  $pp \rightarrow \ell^+\ell^-$ , and low energy neutrino-nucleus coherent scattering measurements [25] are also sensitive to these LQ-induced interactions. NLO QCD corrections to the neutral DY process have been computed in the context of LQ models in Refs. [26, 27]. For detailed bounds obtained in this way, see *e.g.*, Ref. [21], and the Heavy Boson Particle Listings under ‘‘Indirect Limits for Leptoquarks’’, and the references therein.

The two-quark two-lepton interactions arising from the LQ exchanges in Eq.(93.1) and Eq.(93.2) can also be interpreted as contributions to more general dimension-six operators within the framework of the SM Effective Field Theory (SMEFT). See *e.g.*, Refs. [28, 29] for reviews. A complete catalog of SM gauge-invariant dimension-six operators can be found in Refs. [30, 31]. A computation of the one-loop anomalous dimension matrix for SMEFT operators are found in Refs. [32–34]. LQ-induced two-quark two-lepton interactions may cause the lepton flavor non-universality in the heavy quark decays. In particular, models with TeV-scale LQs may accommodate solutions to the  $R(D)$  and  $R(D^*)$  anomaly [13] observed in the semi-leptonic  $b \rightarrow c$  decays.

Collider experiments provide direct limits on the LQ states through limits on the pair- and single-production cross sections. Among these, constraints on single-production often yield limits

severer than those on pair-production. This is because, when particles colliding in the collider interact directly and strongly enough with heavy LQ particles, the energy required for the LQ production is lower in the single-production processes. Conversely, if the direct interaction between the colliding particles and LQs is weak, constraints from pair-production processes become more relevant.

LQs are produced singly in  $ep$  collisions through

$$e + q \rightarrow \text{LQ}, \quad (93.3)$$

and at hadron colliders through [35],

$$g + q \rightarrow \text{LQ} + \ell. \quad (93.4)$$

Depending on the LQ coupling with  $q\ell$ , the LQ single-production process (93.4) allows extending the mass reach higher than the mass reach of the pair-production process [36]. The NLO computations for the single-production of the scalar LQ states at the LHC energies have been performed in Refs. [37–40]. Since protons contain leptons inside, it is possible to target lepton-induced processes (93.3) at high energy  $pp$  colliders. For a scalar LQ, the leading-order single-production cross section of the parton process (93.3) may be written as

$$\hat{\sigma}_{\text{LO}}[eq \rightarrow \text{LQ}] = \frac{\pi\lambda^2}{4}\delta(\hat{s} - M_{\text{LQ}}^2). \quad (93.5)$$

The LQ Yukawa coupling is denoted by  $\lambda$ . The single LQ production cross sections induced from the lepton-quark collisions at the LHC have been computed at LO in Refs. [41–43] and at NLO in Ref. [44]. Ref. [45] performed searches for the LQ states produced in lepton-quark collisions at the LHC.

Pair-production of LQs has been studied at LHC, Tevatron and LEP. The LQ pair-production cross sections in  $e^+e^-$  collisions depend on the LQ  $SU(2)_W \times U(1)_Y$  quantum numbers and Yukawa coupling with electron [46]. For a scalar LQ, the leading-order pair-production cross sections of the parton processes at hadron colliders

$$\begin{aligned} q + \bar{q} &\rightarrow \text{LQ} + \overline{\text{LQ}} \\ g + g &\rightarrow \text{LQ} + \overline{\text{LQ}} \end{aligned} \quad (93.6)$$

may be written as [47]

$$\begin{aligned} \hat{\sigma}_{\text{LO}}[q\bar{q} \rightarrow \text{LQ} + \overline{\text{LQ}}] &= \frac{2\alpha_s^2\pi}{27\hat{s}}\beta^3, \\ \hat{\sigma}_{\text{LO}}[gg \rightarrow \text{LQ} + \overline{\text{LQ}}] &= \frac{\alpha_s^2\pi}{96\hat{s}}\left[\beta(41 - 31\beta^2) + (18\beta^2 - \beta^4 - 17)\log\frac{1+\beta}{1-\beta}\right]. \end{aligned} \quad (93.7)$$

Here  $\sqrt{\hat{s}}$  is the invariant energy of the parton subprocess, and  $\beta \equiv \sqrt{1 - 4M_{\text{LQ}}^2/\hat{s}}$ . The QCD gauge coupling is given by

$$\alpha_s \equiv \frac{g_s^2}{4\pi}. \quad (93.8)$$

The cross sections of the pair-productions of scalar LQs in  $pp$  collisions at the LHC energies have been computed in Refs. [48, 49] at the next-to-leading order (NLO) in QCD. The gauge couplings of a scalar LQ are determined uniquely according to its quantum numbers in Table 93.1. Since all of the

LQ states belong to color-triplet representation, the QCD-induced scalar LQ pair-production cross section at the Tevatron and LHC can be determined solely as a function of the LQ mass without making further assumptions if we are able to neglect contributions from electroweak and Yukawa interactions in the parton cross sections. This is in contrast to the indirect or single-production limits, which give constraints in the LQ mass-coupling plane.

Vector LQ pair-production calculation often violate perturbative unitarity at high energies. Ultraviolet (UV) completion is required, either via extending gauge symmetries (treating vector LQs as gauge bosons) or compositeness (treating them as bound states). Additional heavy particles are typically introduced in both scenarios. Magnetic-dipole and electric-quadrupole interactions of vector LQs are not fixed by gauge quantum numbers [50]. LHC searches often assume gluon-mediated diagrams dominate near threshold, with two benchmark chromomagnetic dipole moments: Yang-Mills case ( $\kappa = 1$ ) and minimal-coupling case ( $\kappa = 0$ ).

Due to the typical decay of the LQ into charged and neutral leptons and quarks, the searches for the LQ states in collider experiments are carried on in signatures including high  $p_T$  charged leptons, high  $E_T$  jets and large missing transverse energy. Additionally, searches for pair-produced LQs are often organized by the decay mode of the pair of LQs, via the decay parameter  $\beta$ , which represents the branching fraction into a charged lepton vs a neutrino:  $\beta = 1$  for LQs decaying into a charged lepton with 100% branching fraction,  $\beta = 0.5$  for LQs decaying into a charged lepton with 50% branching fraction. It is worth noting that organizing LQs by flavor quantum number first before organizing them by gauge quantum number is becoming more common and advantageous because it relates more closely to some of the experimental searches being performed at the hadron colliders. See Ref. [21] for a comprehensive review on the LQ phenomenology in precision experiments and particle colliders.

Since the previous versions of this review, both ATLAS and CMS continue to update their results concerning searches for pair-productions of first, second, and third generation LQs and LQ states which couple only with the  $i$ -th generation quarks and the  $j$ -th generation leptons ( $i \neq j$ ) without causing conflicts with severe indirect constraints. The datasets were almost all collected at center of mass energy of 13 TeV and corresponding to the latest integrated luminosity collected before the shutdown of the LHC occurring in 2019 and 2020. Older results from the Tevatron run can be found here: [51–54].

Current results extend previous mass limits for scalar LQs to  $> 1435$  GeV (first generation, CMS,  $\beta = 1$ ,  $\sqrt{s} = 13$  TeV) and  $> 1270$  GeV (first generation, CMS,  $\beta = 0.5$ ,  $\sqrt{s} = 13$  TeV) [55];  $> 1800$  GeV (first generation, ATLAS,  $\beta = 1$ ,  $\sqrt{s} = 13$  TeV) [56] and  $> 1290$  GeV (first generation, ATLAS,  $\beta = 0.5$ ,  $\sqrt{s} = 13$  TeV) [57];  $> 1530$  GeV (second generation, CMS,  $\beta = 1$ ,  $\sqrt{s} = 13$  TeV) and  $> 1285$  GeV (second generation, CMS,  $\beta = 0.5$ ,  $\sqrt{s} = 13$  TeV) [58]; and  $> 1700$  GeV (second generation, ATLAS,  $\beta = 1$ ,  $\sqrt{s} = 13$  TeV) [56] and  $> 1230$  GeV (second generation, ATLAS,  $\beta = 0.5$ ,  $\sqrt{s} = 13$  TeV) [57]. All limits are presented at 95% confidence level (C.L.).

As for third generation LQs, CMS results are the following: 1) assuming that all LQs decay to a top quark and a  $\tau$  lepton, the existence of pair-produced, third-generation LQ up to a mass of 1120 GeV ( $\beta = 1$ ,  $\sqrt{s} = 13$  TeV) is excluded at 95% C.L. [59]; 2) assuming that all LQs decay to a bottom quark and a  $\tau$  lepton, the existence of pair-produced, third-generation LQ up to a mass of 1020 GeV ( $\beta = 1$ ,  $\sqrt{s} = 13$  TeV) is excluded at 95% C.L. [60]; 3) assuming that all LQs decay to a bottom quark and a  $\tau$  neutrino, the existence of pair-produced, third-generation LQ up to a mass of 1185 GeV ( $\beta = 0$ ,  $\sqrt{s} = 13$  TeV) is excluded at 95% C.L. [61]. In [62] signatures of  $t\tau\nu b$  and  $t\tau\nu$  were analyzed in the context of searches for scalar LQ of charge  $(-1/3)e$  coupling to  $t\tau$  or  $b\nu$ , or a vector particle of charge  $(2/3)e$ , coupling to  $t\nu$  or  $b\tau$ . These choices are motivated by models that can explain a series of anomalies observed in the measurement of B meson decays. The data are found to be in agreement with the SM prediction. Lower limits at 95% C.L. are set on the LQ

mass in the range 0.98–1.73 TeV, depending on the LQ spin and its coupling  $\lambda$  to a lepton and a quark, and assuming equal couplings for the two LQ decay modes considered.

In [63] ATLAS present the result of searches for pair-production of third-generation scalar LQs decaying into a top quark and a  $\tau$ -lepton, using  $139 \text{ fb}^{-1}$  of data collected at 13 TeV. Scalar LQs decaying exclusively into  $t\tau$  are excluded up to masses of 1.43 TeV while, for a branching fraction of 50% into  $t\tau$ , the lower mass limit is 1.22 TeV. In [64] and [65] ATLAS searched for pair-produced scalar or vector LQs decaying into a  $b$ -quark and a  $\tau$ -lepton. Scalar LQ masses below 1.46 TeV are excluded assuming a 100% branching ratio, while for vector LQs the corresponding limit is 1.91 TeV (1.65 TeV) in the Yang–Mills  $\kappa = 1$  (minimal-coupling  $\kappa = 0$ ) scenario. Additionally, a search for pair-production of LQs with decays into third-generation leptons and quarks in final states with hadronically decaying  $\tau$  leptons,  $b$ -jets, and missing transverse momentum was performed in [66]: depending on the branching fraction into charged leptons, LQs with masses up to around 1.25 TeV can be excluded at the 95% C.L. for the case of scalar LQs and up to 1.8 TeV (1.5 TeV) for vector LQs in a Yang–Mills (minimal-coupling) scenario.

As we explained before, the LQ models which couples only to quarks of the  $i$ -th generation and leptons of the  $j$ -th generation ( $i \neq j$ ) are attracting attention. In this framework, in [67] and [59] CMS presents a search for pair-production of LQs coupled to a top quark and a leptons. As no deviation from the SM prediction was observed, scalar LQs decaying exclusively into top quark and lepton are excluded below 1.12 – 1.42 TeV depending on the lepton flavor. In [68] ATLAS conducted a search for pair-production of LQs, each decaying into first and second generation leptons and a third generation quarks. This is part of LQ search using ATLAS data to investigate cross- generational couplings. All possible decays of the pair-produced LQs into quarks of the third generation and charged or neutral leptons of the first or second generation with exactly one electron or muon in the final state are investigated. No significant deviations from the SM expectation are observed. Upper limits on the production cross-section are provided for different models as a function of the LQ mass and the branching ratio of the LQ into the charged or neutral lepton. Some of these models have the goal of providing an explanation for the recent  $B$ -anomalies. In such models, a vector LQ decays into charged and neutral leptons of the second generation with a similar branching fraction. Lower limits of 1.98 TeV (1.71 TeV) are set on the vector leptoquark mass for Yang-Mills (minimal-coupling) scenario with  $B(b\mu) = B(t\nu) = 0.5$ . In [69] CMS search for pair-production of scalar and vector LQs decaying to  $\mu b$ . Assuming  $B(\mu b) = 1$ , Scalar LQs with  $M_{LQ} < 1.81$  TeV are excluded with 95% C.L.; Vector LQs with  $M_{LQ} < 2.46$  TeV (2.12 TeV) are excluded in the Yang-Mills (minimal) coupling scenario. CMS also set limits on the  $t$ -channel vector LQ exchange  $\tau\tau$  production amplitude [70] and  $\tau\nu$  production amplitude [71] in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. Their limits on the dimensionless vector LQ coupling to  $q\tau$  and  $q\nu$  range from 1 for  $M_{LQ} = 1$  TeV to 6 for  $M_{LQ} = 5$  TeV, depending on the scenario. ATLAS search result for pair-production of scalar and vector LQs decaying to  $te$  or  $t\mu$  have been reported in [72]. Under the assumption of exclusive decays into  $te$  ( $t\mu$ ), the lower limit on the scalar LQ mass is at 1.58 TeV (1.59 TeV), on the vector LQ mass with Yang-Mills coupling at 1.95 TeV (1.95 TeV), and on the vector LQ mass with minimal-coupling at 1.67 TeV (1.67 TeV). In [73] ATLAS have reported their results on searches for pair-production of scalar LQ decaying into  $c\tau$ . LQs with masses below 1.3 TeV are excluded at 95% C.L. when  $B(c\tau) = 1$ . A statistical combination of ATLAS searches for pair-produced LQs decaying into a third generation quark ( $t$  or  $b$ ) and any charged or neutral lepton has been reported in [74]. The lower limits on the masses of scalar LQs range from 1.23 TeV to 1.73 TeV, depending on the branching ratio, LQ charge and flavor. Limits are also placed on benchmark vector LQ models. The mass limit on the charge  $(2/3)e$  vector LQ ranges from 1.84 TeV to 1.98 TeV (from 1.58 TeV to 1.71 TeV) for 50% branching fraction, depending on LQ flavor in the Yang-Mills case  $\kappa = 1$  (minimal-coupling case  $\kappa = 0$ ).

Previous search results from CMS for squarks and gluinos have been reinterpreted to constrain models of LQ pair-production [75]. For a vector LQ decaying to  $t\nu$  with 50% branching fraction, masses below 1.53 TeV are excluded assuming the Yang-Mills case  $\kappa = 1$ , or 1.115 TeV in the minimal-coupling case  $\kappa = 0$ . These results and the ones in [76] were updated in [61] where searches for phenomena beyond the standard model (BSM) were performed using events with hadronic jets and significant transverse momentum imbalance to constrain a range of BSM models including the pair-production of LQs each decaying to a neutrino and a top, bottom, or light-flavor quark.

Searches for first generation LQ singly produced were performed by the HERA experiments. Since the leptoquark single-production cross section depends on its Yukawa coupling, the LQ mass limits from HERA are usually displayed in the mass-coupling plane. For leptoquark Yukawa coupling  $\lambda = 0.1$ , early ZEUS Collaboration bounds on the first-generation LQ range from 248 to 290 GeV, depending on the LQ species [77]. The ZEUS Collaboration has released a paper [78] where data corresponding to a luminosity of around  $1 \text{ fb}^{-1}$  have been used in the framework of  $eeqq$  contact interactions (CI) to set limits on possible high-energy contributions beyond the SM to electron-quark scattering. The analysis of the  $ep$  data has been based on simultaneous fits of parton distribution functions including contributions of Contact Interaction (CI) couplings to  $ep$  scattering. Several general CI models and scenarios with heavy leptoquarks were considered. As unambiguous deviations from the SM cannot be established, limits for CI compositeness scales and LQ mass scales were set that are in the TeV range. The H1 Collaboration has a comprehensive summary of searches for first generation LQs using the full data sample collected in  $ep$  collisions at HERA ( $446 \text{ pb}^{-1}$ ). No evidence of production of LQs was observed in final states with a large transverse momentum electron or large missing transverse momentum. For a coupling strength  $\lambda = 0.3$ , first generation leptoquarks with masses up to 800 GeV are excluded at 95% C.L. [79].

At the LHC, the CMS collaboration performed searches for single-production of first and second generation LQs [80], which is complementary to the HERA searches in the high  $\lambda$  region (for coupling strength  $\lambda = 1.0$ , first generation leptoquarks are excluded for masses up to 1.73 TeV and second generation leptoquark are excluded up to masses of 530 GeV). CMS also searched for third generation LQ decaying into  $\tau$  and bottom in [81]. Assuming unit Yukawa coupling ( $\lambda$ ), a third generation scalar LQ is excluded for masses below 740 GeV. Limits are also set on  $\lambda$  of the hypothesized LQ as a function of its mass. Above  $\lambda = 1.4$ , the results provide the best upper limit on the mass of a third-generation scalar LQ decaying to a  $\tau$  lepton and a bottom quark. In [82] a CMS search is presented for a LQ coupled exclusively to  $b\tau$ . Events with  $\tau$  and a varying number of jets originating from  $b$  are considered, targeting the single- and pair-production of LQs, as well as non-resonant  $t$ -channel LQ exchange. An excess is observed and for a benchmark LQ model with  $M_{\text{LQ}} = 2 \text{ TeV}$  and its coupling with  $b\tau$  of 2.5, the excess reaches a local significance of  $2.8\sigma$ . LQs are excluded below masses of 1.22–1.88 TeV for different LQ models and varying coupling strengths up to 2.5. In [64] and [65] ATLAS searched for single-production of vector LQ with electric charge of  $(2/3)e$  and scalar LQ with an electric charge of  $(4/3)e$  via  $bg$  fusion. For single vector LQ production Two models are considered: the Yang–Mills and Minimal-coupling models. Vector LQs with a mass below 1.58 TeV (1.35 TeV) are excluded in the Yang–Mills (minimal-coupling) scenario, for a LQ coupling of 1.0 and below 2.05 TeV (1.99 TeV) for a LQ coupling of 2.5. scalar LQ masses below 1.28 TeV (1.53 TeV) are excluded for a LQ Yukawa coupling of 1.0 (2.5). Single-production of a multigenerational scalar LQ has also been searched by ATLAS in [83] via charged-lepton-flavor-violating process. In [45] CMS search results for scalar LQ singly produced via quark- $\tau$  fusion have been reported.

Searches for LQ will continue with more LHC data, particularly in light of the renewed interest in this type of particle to explain violation of lepton flavor universality and other anomalies, which point to explanations laying outside the Standard Model.

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