94. Leptoquarks

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Leptoquarks are hypothetical particles carrying both baryon number (B) and lepton number (L). The possible quantum numbers of leptoquark states can be restricted by assuming that their direct interactions with the ordinary Standard Model (SM) fermions are dimensionless and invariant under the SM gauge group. Table 94.1 shows the list of all possible quantum numbers with this assumption [1]. The columns of $SU(3)_C$, $SU(2)_W$, and $U(1)_Y$ in Table 94.1 indicate the QCD representation, the weak isospin representation, and the weak hypercharge, respectively. The spin of a leptoquark state is taken to be 1 (vector leptoquark) or 0 (scalar leptoquark).

Table 94.1: Possible leptoquarks 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	$\bar{q}^c_L \ell_L$ or $\bar{u}^c_R e_R$
0	-2	$\bar{3}$	1	4/3	$\bar{d}^c_R e_R$
0	-2	$\bar{3}$	3	1/3	$\bar{q}^c_L \ell_L$
1	-2	$\bar{3}$	2	5/6	$\bar{q}^c_L \gamma^\mu e_R$ or $\bar{d}^c_R \gamma^\mu \ell_L$
1	-2	$\bar{3}$	2	$-1/6$	$\bar{u}^c_R \gamma^\mu \ell_L$
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	$\bar{q}_L \gamma^\mu \ell_L$

If we do not require leptoquark states to couple directly with SM fermions, different assignments of quantum numbers become possible [2,3].

Leptoquark states are expected to exist in various extensions of the SM. The Pati-Salam model [4] is an example predicting the existence of a leptoquark state. Leptoquark states also exist in grand unification theories based on $SU(5)$ [5], $SO(10)$ [6] which includes Pati-Salam color $SU(4)$, and larger gauge groups. The existence of leptoquarks at TeV-scale also affect the renormalization group of the standard model gauge coupling strengths and may allow for the gauge coupling unification required by the grand unification theories [7]. Scalar quarks in supersymmetric models with R-parity violation may also have leptoquark-type Yukawa couplings. The bounds on the leptoquark states can therefore be applied to constrain R-parity-violating supersymmetric models [8,9]. Scalar leptoquarks are expected to exist at the TeV scale in extended technicolor models [10, 11] where leptoquark states appear as the bound states of techni-fermions. Compositeness of quarks and leptons also provides examples of models which may have light leptoquark states [12].

Bounds on leptoquark states are obtained both directly and indirectly. Direct limits are from their production cross sections at colliders, while indirect limits are calculated from bounds on leptoquark-induced two-quark two-lepton interactions, which are obtained from low-energy experiments, or from collider experiments below threshold. The quantum number assignment of Table 94.1 allows several leptoquark states to couple to both left- and right-handed quarks simultaneously. Such leptoquark states are called non-chiral and may cause low-energy interactions

$$(\bar{u}_R q_{Li})(\bar{e}_R \ell_{Lj})\epsilon^{ij} \qquad (\bar{d}_R q_{Li})(\bar{\ell}^i_L e_R)\,. \tag{94.1}$$

Here i, j are indices for the weak isospin. These two-quark two-lepton interactions affect the $(\pi \to e\nu)/(\pi \to \mu\nu)$ ratio [13]. Non-chiral scalar leptoquarks also contribute to the anomalous magnetic moments of charged leptons [14, 15]. On the other hand, the exchanges of the chiral leptoquarks produce effective two-quark two-lepton interactions

$$\begin{aligned} &(\bar{q}^i_L\gamma^\mu q_{Li})(\bar{\ell}^j_L\gamma_\mu\ell_{Lj}), && (\bar{q}^i_L\gamma^\mu q_{Li})(\bar{e}_R\gamma_\mu e_R), && (\bar{q}^i_L\gamma^\mu(\vec{\sigma})_i{}^j q_{Lj})\cdot(\bar{\ell}^k_L\gamma_\mu(\vec{\sigma})_k{}^l\ell_{Ll}), \\ &(\bar{u}_R\gamma^\mu u_R)(\bar{\ell}^j_L\gamma_\mu\ell_{Lj}), && (\bar{u}_R\gamma^\mu u_R)(\bar{e}_R\gamma_\mu e_R), \\ &(\bar{d}_R\gamma^\mu d_R)(\bar{\ell}^j_L\gamma_\mu\ell_{Lj}), && (\bar{d}_R\gamma^\mu d_R)(\bar{e}_R\gamma_\mu e_R) \end{aligned} \tag{94.2}$$

below the leptoquark mass scale. Note that labels for the generations of quarks and leptons are suppressed in (94.1) and (94.2). If a leptoquark couples to quarks (leptons) belonging to more than a single generation in the mass eigenbasis, it can induce two-quark two-lepton interactions causing flavor-changing neutral currents (lepton-family-number violations). Since indirect limits provide more stringent constraints on non-chiral or flavor-violating leptoquarks, in the searches of leptoquark states at collider experiments, it is often assumed that a leptoquark state couples only to a single generation of quarks and a single generation of leptons in a chiral interaction, for which indirect limits become much weaker. Additionally, this assumption gives strong constraints on models of leptoquarks.

Refs. [16–18] give extensive lists of the bounds on the leptoquark-induced two-quark two-lepton interactions. For the isoscalar scalar and vector leptoquarks 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 $\lambda^2 < 0.07 \times (M_{\rm LQ}/1~{\rm TeV})^2$ for S_0, and $\lambda^2 < 0.4 \times (M_{\rm LQ}/1~{\rm TeV})^2$ for V_0 ($\lambda^2 < 0.7 \times (M_{\rm LQ}/1~{\rm TeV})^2$ for S_0, and $\lambda^2 < 0.5 \times (M_{\rm LQ}/1~{\rm TeV})^2$ for V_0) with λ being the leptoquark coupling strength, can be derived from the limits listed in Ref. [18]. See also Refs. [19, 20] for earlier studies. The e^+e^- collider experiments are sensitive to the indirect effects coming from t- and u-channel exchanges of leptoquarks in the $e^+e^- \to q\bar{q}$ process. The HERA experiments give bounds on the leptoquark-induced two-quark two-lepton interaction. It should also be stressed that the measurements of the high-mass Drell-Yan cross sections, $pp \to \ell\nu$ and $pp \to \ell^+\ell^-$, are also sensitive to these leptoquark-induced interactions. For detailed bounds obtained in this way, see *e.g.,* Ref. [17], and the Heavy Boson Particle Listings for "Indirect Limits for Leptoquarks" and their references.

Note that the two-quark two-lepton interactions arising from the leptoquark exchanges in Eq.(94.1) and Eq.(94.2) can also be regarded as a part of more general dimension-six operators in the context of low-energy standard-model effective field theory (SMEFT). For a complete list of SM gauge-invariant dimension-six operators, see [21,22]. A computation of the one-loop anomalous dimension matrix for SMEFT operators are found in Refs. [23–25]. The leptoquark induced two-quark two-lepton interactions often cause lepton-flavor non-universalities in heavy quark decays. The $R(D)$, $R(D^*)$ anomaly observed in the semi-leptonic B decays [26] may be explained in models with TeV scale leptoquarks.

Collider experiments provide direct limits on the leptoquark states through limits on the pair- and single-production cross sections. The leading-order cross sections of the parton processes

$$\begin{aligned} q + \bar{q} &\to {\rm LQ} + \overline{\rm LQ} \\ g + g &\to {\rm LQ} + \overline{\rm LQ} \\ e + q &\to {\rm LQ} \end{aligned} \tag{94.3}$$

may be written as [27]

$$\hat{\sigma}_{\rm LO}\Big[q\bar{q} \to {\rm LQ} + \overline{\rm LQ}\Big] = \frac{2\alpha_s^2\pi}{27\hat{s}}\beta^3,$$
$$\hat{\sigma}_{\rm LO}\Big[gg \to {\rm LQ} + \overline{\rm LQ}\Big] = \frac{\alpha_s^2\pi}{96\hat{s}} \times \Big[\beta(41 - 31\beta^2) + (18\beta^2 - \beta^4 - 17)\log\frac{1+\beta}{1-\beta}\Big],$$
$$\hat{\sigma}_{\rm LO}\Big[eq \to {\rm LQ}\Big] = \frac{\pi\lambda^2}{4}\delta(\hat{s} - M_{\rm LQ}^2) \tag{94.4}$$

for a scalar leptoquark. Here $\sqrt{\hat{s}}$ is the invariant energy of the parton subprocess, and $\beta \equiv \sqrt{1 - 4M_{\rm LQ}^2/\hat{s}}$. The leptoquark Yukawa coupling is given by λ. The cross sections of the pair productions of scalar leptoquarks in pp collisions at the LHC energies have been computed in Refs. [28,29] at the next-to-leading order in QCD. Leptoquarks are also produced singly at hadron colliders through $g + q \to {\rm LQ} + \ell$ [30], which allows extending to higher masses the collider reach in the leptoquark search [31], depending on the leptoquark Yukawa coupling. The next-to-leading order computations for the single production of the leptoquark states at the LHC energies have been performed in Refs. [32–35]. Since protons contain leptons inside, it is possible to target lepton-induced processes at high energy pp colliders. The single leptoquark production cross sections induced from the lepton-quark collisions at the LHC have been computed in Refs. [36,37]. Ref. [38] performed searches for the leptoquark states produced in lepton-quark collisions at the LHC.

See Ref. [17] for a comprehensive review on the leptoquark phenomenology in precision experiments and particle colliders.

Leptoquark states which couple only to left- or right-handed quarks are called chiral leptoquarks. Leptoquark states which couple only to the first (second, third) generation are referred as the first- (second-, third-) generation leptoquarks.

The LHC, Tevatron and LEP experiments have been searching for pair production of the leptoquark states, which arises from the leptoquark gauge interaction. Due to the typical decay of the leptoquark into charged and neutral leptons and quarks, the searches 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 β, which represents the branching fraction into a charge 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. The gauge couplings of a scalar leptoquark are determined uniquely according to its quantum numbers in Table 94.1. Since all of the leptoquark states belong to color-triplet representation, the scalar leptoquark QCD-induced pair-production cross section at the Tevatron and LHC can be determined solely as a function of the leptoquark mass without making further assumptions. This is in contrast to the indirect or single-production limits, which give constraints in the leptoquark mass-coupling plane.

Older results from the Tevatron run can be found here: [39–42].

Since the previous version of this review, both ATLAS and CMS continue to update their results concerning searches for first, second, and third generation LQs and leptoquark 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.

It is worthy to note 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. The traditional nomenclature for 1st, 2nd, and 3rd generation LQ encourages only looking for the diagonal elements in a flavor matrix of possibilities, which has been the traditional experimental search strategy.

Current results extend previous mass limits for scalar leptoquarks to $>$ 1435 GeV (first generation, CMS, β =1, $\sqrt{s} = 13$ TeV) and $>$ 1270 GeV(first generation, CMS, β =0.5,$\sqrt{s} = 13$ TeV) [43]; $>$ 1800 GeV (first generation, ATLAS, β =1, $\sqrt{s} = 13$ TeV) [44] and $>$ 1290 GeV (first generation, ATLAS, β =0.5, $\sqrt{s} = 13$ TeV) [45]; $>$ 1530 GeV (second generation, CMS, β =1, $\sqrt{s} = 13$ TeV) and $>$ 1285 GeV (second generation, CMS, β =0.5, $\sqrt{s} = 13$ TeV) [46]; and $>$ 1700 GeV (second generation, ATLAS, β =1,$\sqrt{s} = 13$ TeV) [44] and $>$ 1230 GeV (second generation, ATLAS, β =0.5,$\sqrt{s} = 13$ TeV) [45]. All limits are presented at 95% C.L.

As for third generation leptoquarks, CMS results are the following: 1) assuming that all leptoquarks decay to a top quark and a τ lepton, the existence of pair produced, third-generation leptoquark up to a mass of 1120 GeV (β =1, 13 TeV) is excluded at 95% confidence level [47]; 2) assuming that all leptoquarks decay to a bottom quark and a τ lepton, the existence of pair produced, third-generation leptoquark up to a mass of 1020 GeV (β =1, 13 TeV) is excluded at 95% confidence level [48]; 3) assuming that all leptoquarks decay to a bottom quark and a τ neutrino, the existence of pair produced, third-generation leptoquark up to a mass of 1185 GeV (β =0, 13 TeV) is excluded at 95% confidence level [49]. In a recent paper [50] signatures of top quark τ lepton ν bottom and top τ ν - not previously explored in dedicated searches, were analyzed in the context of searches for scalar leptoquark of charge -1/3e coupling to a top quark plus a τ lepton (tτ) or a bottom quark plus a neutrino (bν), or a vector particle of charge +2/3e, coupling to tν or bτ. 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 standard model prediction. Lower limits at 95% confidence level are set on the LQ mass in the range 0.98–1.73 TeV, depending on the LQ spin and its coupling λ to a lepton and a quark, and assuming equal couplings for the two LQ decay modes considered. These are the most stringent constraints to date on the existence of leptoquarks in this scenario.

In [51] ATLAS present the result of searches for pair production of third-generation scalar leptoquarks decaying into a top quark and a τ-lepton, using 139 fb^{-1} of data collected at 13 TeV. Scalar leptoquarks decaying exclusively into tτ are excluded up to masses of 1.43 TeV while, for a branching fraction of 50% into tτ , the lower mass limit is 1.22 TeV. In two recent papers [52] and [53] ATLAS searched for pair-produced scalar or vector leptoquarks decaying into a b-quark and a τ-lepton and single production of vector leptoquarks with electric charge of 2/3e and scalar leptoquarks with an electric charge of 4/3e. For pair production of scalar leptoquarks, masses below 1490 GeV are excluded assuming a 100% branching ratio, while for vector leptoquarks the corresponding limit is 1690 GeV (1960 GeV) in the minimal-coupling (Yang–Mills) scenario. For single vector leptoquark production two models are considered: the Yang–Mills and Minimal coupling models. In the Yang–Mills (Minimal coupling) scenario, vector leptoquarks with a mass below 1.58 (1.35) TeV are excluded for a gauge coupling of 1.0 and below 2.05 (1.99) TeV for a gauge coupling of 2.5. In the case of single scalar leptoquark production, masses below 1.28 TeV (1.53 TeV) are excluded for a Yukawa coupling of 1.0 (2.5). Additionally, a search for pair production of leptoquarks with decays into third-generation leptons and quarks. in final states with hadronically decaying τ leptons, b-jets, and missing transverse momentum was performed in [54]: depending on the branching fraction into charged leptons, leptoquarks with masses up to around 1.25 TeV can be excluded at the 95% confidence level for the case of scalar leptoquarks and up to 1.8 TeV (1.5 TeV) for vector leptoquarks in a Yang–Mills (minimal-coupling) scenario.

It is also possible to consider leptoquark 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. Such couplings have received renewed attention because they may provide an explanation to anomalies in rare $B - meson$ decays and the anomalous magnetic moment of the muon. See Ref. [55, 56] and [57] and references therein for collider search strategies and limits on the pair production cross sections of this class of leptoquark states. In this framework, in [58] and [47] CMS presents a non-traditional search for pair production of LQs coupled to a top quark and a leptons. As no deviation from the Standard Model 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 [59] ATLAS conducted a search for pair production of scalar and vector leptoquarks, each decaying into first and second generation leptons and a third generation quarks. This is part of leptoquark search using ATLAS data to investigate cross- generational couplings that could provide explanations for recently observed anomalies in B meson decays. All possible decays of the pair-produced leptoquarks 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 Standard Model expectation are observed. Upper limits on the production cross-section are provided for different models as a function of the leptoquark mass and the branching ratio of the leptoquark 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 leptoquark decays into charged and neutral leptons of the second generation with a similar branching fraction. Lower limits of 1.9 TeV and 1.7 TeV are set on the leptoquark mass for these two models.

The magnetic-dipole-type and the electric-quadrupole-type interactions of a vector leptoquark are not determined even if we fix its gauge quantum numbers as listed in the Table 94.1 [60]. The production of vector leptoquarks depends in general on additional assumptions, where the leptoquark couplings and their pair production cross sections are enhanced relative to the scalar leptoquark contributions. The most stringent limits on vector LQ production are now from CMS [61] where previous searches for squarks and gluinos have been reinterpreted to constrain models of leptoquark production. LQ masses below 1530 GeV are excluded assuming the Yang-Mills case with coupling $\kappa = 1$, or 1115 GeV in the minimal coupling case where $\kappa = 0$, placing the most stringent constraint to date from pair production of vector LQs. These results and the ones in [62] were updated in [49] 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 scalar and vector leptoquarks each decaying to a neutrino and a top, bottom, or light-flavor quark.

The leptoquark pair-production cross sections in e^+e^- collisions depend on the leptoquark $SU(2) \times U(1)$ quantum numbers and Yukawa coupling with electron [63].

Searches for first generation leptoquark singly produced were performed by the HERA experiments. Since the leptoquark single-production cross section depends on its Yukawa coupling, the leptoquark 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 leptoquarks range from 248 to 290 GeV, depending on the leptoquark species [64]. The ZEUS Collaboration has recently released a new paper [65] where data corresponding to a luminosity of around 1 fb^{-1} have been used in the framework of *eeqq* contact interactions (CI) to set limits on possible high-energy contributions beyond the Standard Model 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 leptoquarks using the full data sample collected in *ep* collisions at HERA (446 pb^{-1}). No evidence of production of leptoquarks 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. [66].

At the LHC, the CMS collaboration performed searches for single production of first and second generation leptoquarks [67], which is complementary to the HERA searches in the high λ 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 recently searched for third generation LQ decaying into τ and *bottom* in [68]. Assuming unit Yukawa coupling (λ), a third generation scalar leptoquark is excluded for masses below 740 GeV. Limits are also set on λ of the hypothesized leptoquark 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 leptoquark decaying to a τ lepton and a bottom quark.

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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