60. 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 SM fermions are dimensionless and invariant under the standard model (SM) gauge group. Table 60.1 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 60.1 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 60.1: 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 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. 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. Scalar leptoquarks are expected to exist at TeV scale in extended technicolor models [7,8] 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 [9].

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 the bounds on the leptoquark-induced four-fermion interactions, which are obtained from low-energy experiments, or from collider experiments below threshold. These four-fermion interactions often cause lepton-flavor non-universalities in heavy quark decays. Anomalies observed recently in the R_K and R_D ratios [10,11] in the semi-leptonic B decays may be explained in models with TeV scale leptoquarks.

If a leptoquark couples to quarks (leptons) belonging to more than a single generation in the mass eigenbasis, it can induce four-fermion interactions causing flavor-changing neutral currents (lepton-family-number violations). The quantum number assignment of Table 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 four-fermion interactions affecting the $(\pi \to e\nu)/(\pi \to \mu\nu)$ ratio [12]. Non-chiral scalar leptoquarks also contribute to the muon anomalous magnetic moment [13,14]. Since indirect limits provide more stringent constraints on these types of leptoquarks, 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 concrete models of leptoquarks.

Refs. [15,16,17] give extensive lists of the bounds on the leptoquark-induced four-fermion 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 of Ref. 17 read $\lambda^2 < 0.07 \times (M_{\mathrm{LQ}}/1\ \mathrm{TeV})^2$ for S_0, and $\lambda^2 < 0.4 \times (M_{\mathrm{LQ}}/1\ \mathrm{TeV})^2$ for V_0 ($\lambda^2 < 0.7 \times (M_{\mathrm{LQ}}/1\ \mathrm{TeV})^2$ for S_0, and $\lambda^2 < 0.5 \times (M_{\mathrm{LQ}}/1\ \mathrm{TeV})^2$ for V_0) with λ being the leptoquark coupling strength. The e^+e^- 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 four-fermion interaction. For detailed bounds obtained in this way, see the Boson Particle Listings for "Indirect Limits for Leptoquarks" and its references.

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

$$\begin{aligned} & q + \bar{q} \to LQ + \overline{LQ} \\ & g + g \to LQ + \overline{LQ} \\ & e + q \to LQ \end{aligned} \tag{60.1}$$

may be written as [18]

$$\hat{\sigma}_{\rm LO}\Big[q\bar{q} \to {\rm LQ} + \overline{\rm LQ}\Big] = \frac{2\alpha_s^2\pi}{27\hat{s}}\beta^3,$$

$$\hat{\sigma}_{\rm LO}\Big[gg \to {\rm LQ} + \overline{\rm LQ}\Big] = \frac{\alpha_s^2\pi}{96\hat{s}}$$

$$\times \Big[\beta(41 - 31\beta^2) + (18\beta^2 - \beta^4 - 17)\log\frac{1+\beta}{1-\beta}\Big],$$

$$\hat{\sigma}_{\rm LO}\Big[eq \to {\rm LQ}\Big] = \frac{\pi\lambda^2}{4}\delta(\hat{s} - M_{\rm LQ}^2) \qquad (60.2)$$

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. Leptoquarks are also produced singly at hadron colliders through $g + q \to LQ + \ell$ [19], which allows extending to higher masses the collider reach in the leptoquark search [20], depending on the leptoquark Yukawa coupling. See also Ref. [21] 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 search for pair production of the leptoquark states, which arises from the leptoquark gauge interaction. The searches are carried on in signatures including high P_T leptons, E_T jets and large missing transverse energy, due to the typical decay of the leptoquark. The gauge couplings of a scalar leptoquark are determined uniquely according to its quantum numbers in Table 60.1. Since all of the leptoquark states belong to color-triplet representation, the scalar leptoquark 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: [23], [24], [25] and [26].

Current results from the LHC proton-proton collider, running at a center of mass energies of 7, 8 TeV and 13 TeV, extend previous mass limits for scalar leptoquarks to $>$ 1130 GeV (first generation, CMS, β =1, $\sqrt{s} = 13$ TeV) and $>$ 920 GeV(first generation, CMS, β =0.5,$\sqrt{s} = 13$ TeV) [27]; $>$ 1100 GeV (first generation, ATLAS, β =1, $\sqrt{s} = 13$ TeV) [28] and $>$ 900 GeV (first generation, ATLAS, β =0.5, $\sqrt{s} = 8$ TeV - no update at 13 TeV is available at this time) [29]; $>$ 1165 GeV (second generation, CMS, β =1, $\sqrt{s} = 13$ TeV) [30] and $>$ 960 GeV (second generation, CMS, β =0.5, $\sqrt{s} = 13$ TeV) [30]; and $>$ 1050 GeV (second generation, ATLAS, β =1,$\sqrt{s} = 13$ TeV) [28] and $>$ 850 GeV (second generation, ATLAS, β =0.5,$\sqrt{s} = 8$ TeV - no update at 13 TeV is available at this time) [29]. All limits at 95% C.L.

As for third generation leptoquarks, CMS results are the following (using both 8 and 13 TeV run data): 1) assuming that all leptoquarks decay to a top quark and a τ lepton, the existence of pair produced, third-generation leptoquarks up to a mass of 685 GeV (β =1, 8 TeV) is excluded at 95% confidence level [31]; 2) assuming that all leptoquarks decay to a bottom quark and a τ lepton, the existence of pair produced, third-generation leptoquarks up to a mass of 850 GeV (β =1, 13 TeV) is excluded at 95% confidence level [32]; 3)assuming that all leptoquarks decay to a bottom quark and a τ neutrino, the existence of pair produced, third-generation leptoquarks up to a mass of 450 GeV (β =0.5, 8 TeV)is excluded at 95% confidence level [33].

The ATLAS collaboration has a limit on third generation scalar leptoquark for the case of β =1 of 525 GeV [34] and 625 GeV for third-generation leptoquarks in the bottom τ neutrino channel, and 200 $< m_{LQ} <$ 640 GeV in the top τ neutrino channel [34].

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. See Ref. [35] for collider search strategies and present limits on the pair production cross sections of this class of leptoquark states.

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 [36]. The production of vector leptoquarks depends in general on additional assumptions that the leptoquark couplings and their pair-production cross sections are enhanced relative to the scalar leptoquark contributions. 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 [37].

The most stringent searches for the leptoquark single production 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 $\lambda = 0.1$, the ZEUS bounds on the first-generation leptoquarks range from 248 to 290 GeV, depending on the leptoquark species [39]. The H1 Collaboration released 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. [41]. The CMS collaboration performed a search for single production of first and second geneation leptoquarks [42], which is complementary to the HERA searches in the high λ region (for coupling strenght $\lambda = 1.0$, first generation leptoquarks are excluded for masses up to 1.75 TeV).

The search for LQ will continue with more LHC data. Early feasability studies by the LHC experiments ATLAS [44] and CMS [45] indicate that clear signals can be established for masses up to about M_{LQ} 1.3 to 1.4 TeV for first- and second-generation scalar LQ, with a likely final reach 1.5 TeV, for collisions at 14 TeV in the center of mass.

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