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 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 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 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. Vector 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 constraining 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.

If a leptoquark couples to fermions more than a single generation in the mass eigenbasis of the SM fermions, it can induce four-fermion interactions causing flavor-changing neutral currents and 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 [10]. Non-chiral scalar leptoquarks also contribute to the muon anomalous magnetic moment [11,12]. Indirect limits provide stringent constraints on these leptoquarks.

It is therefore often assumed that a leptoquark state couples only to a single generation in a chiral interaction, where indirect limits become much weaker. This assumption gives strong constraints on concrete models of leptoquarks, however. 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. Refs. [13,14] give extensive lists of the bounds on the leptoquark-induced four-fermion interactions. For the isoscalar 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. 13 read $\lambda^2 < 0.03 \times (M_{\rm LQ}/300\ {\rm GeV})^2$ for S_0, and $\lambda^2 < 0.02 \times (M_{\rm LQ}/300\ {\rm GeV})^2$ for V_0 ($\lambda^2 < 5 \times (M_{\rm LQ}/300\ {\rm GeV})^2$ for S_0, and $\lambda^2 < 3 \times (M_{\rm LQ}/300\ {\rm GeV})^2$ 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

$$
\begin{aligned}
&q + \bar{q} \to LQ + \overline{LQ} \\
&g + g \to LQ + \overline{LQ} \\
&e + q \to LQ
\end{aligned}
\tag{1}
$$

may be written as [15]

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

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 $g + q \to LQ + \ell$ [16], which allows extending the collider reach in the leptoquark search [17], depending on the leptoquark Yukawa coupling.

The Tevatron and LEP experiments search for pair production of the leptoquark states, which arises from the leptoquark gauge interaction. The gauge couplings of a scalar leptoquark are determined uniquely according to its quantum numbers in Table 1. Since all of the leptoquark states belong to color-triplet representation, the scalar leptoquark pair-production cross section at Tevatron 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. For the first- and second-generation scalar leptoquark states with decaying branching fraction $B(eq) = 1$ and $B(\mu q) = 1$, the CDF and D0 experiments obtain the lower bounds on the leptoquark mass > 236 GeV (first generation, CDF) [18], > 256 GeV (first generation, D0) [19], > 226 GeV (second generation, CDF) [20], and > 251 GeV (second generation, D0) [21] at 95% CL. On the other hand, 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 [22]. 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. At the Tevatron for instance, since the acceptance for vector and scalar leptoquark detection is similar, limits on the vector leptoquark mass will be more stringent. 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 [23]. The OPAL experiment gives mass bounds on various leptoquark states from the pair-production cross sections [24]. For a second-generation weak-isosinglet weak-hypercharge $-4/3$ scalar-leptoquark state, for example, the OPAL pair-production bound is $M_{\rm LQ} > 100$ GeV at 95% CL.

The searches for the leptoquark single production are performed by the HERA experiments. Since the leptoquark single-production cross section depends on the leptoquark Yukawa

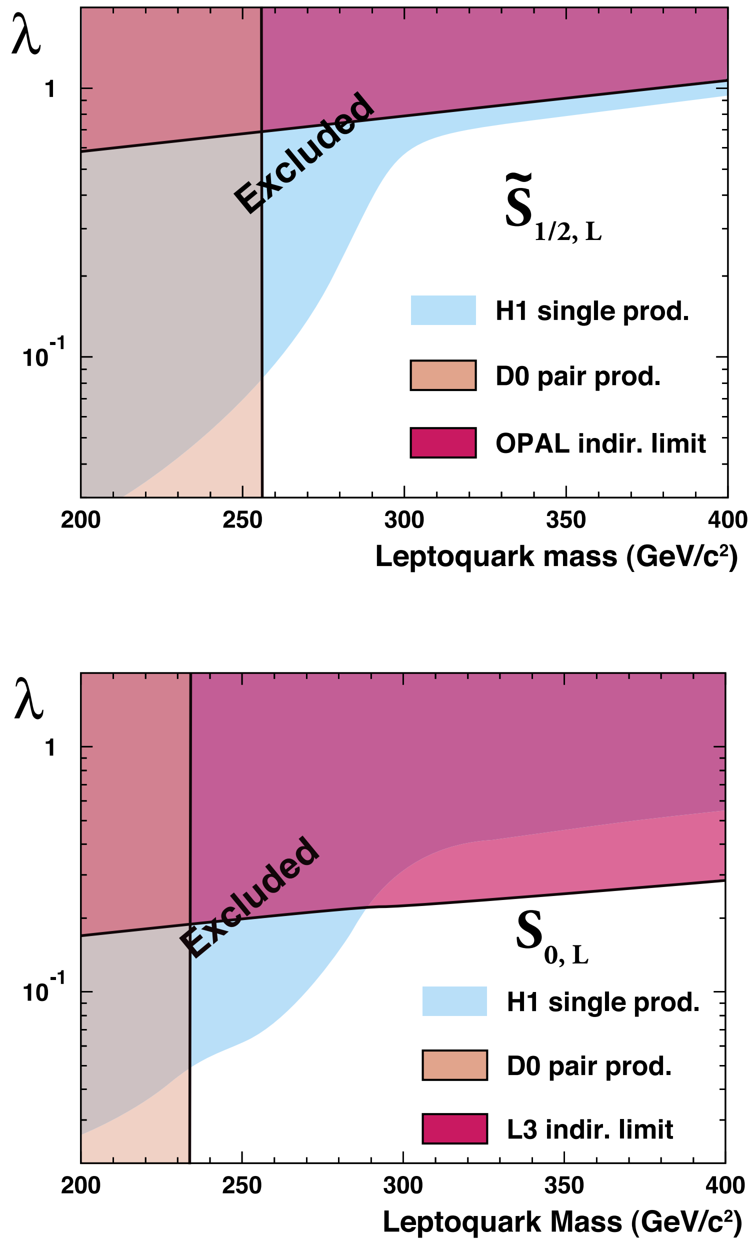

Figure 1: Limits on two typical first-generation scalar leptoquark states in the mass-coupling plane. The upper figure is for a weak-isodoublet, weak-hypercharge 7/6, $3B + L = 0$ leptoquark state, while the lower figure for a weak-isosinglet, weak-hypercharge $-1/3$, $3B + L = 2$ state.

coupling, the leptoquark 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 [25]. Similar bounds are obtained by H1 [26]. The LEP experiments also search for the single production of the leptoquark states from the process $e\gamma \rightarrow LQ + q$.

Fig. 1 summarizes D0, LEP, and H1 limits on two typical first-generation scalar-leptoquark states in the mass-coupling plane [26].

The search for LQ will be continued soon at the CERN LHC. Preliminary feasability studies by the LHC experiments ATLAS [27] and CMS [28] 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 final reach of presumably 1.5 TeV.

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