

Minireview of Leptoquark Searches

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Direct and indirect leptoquark searches at colliders are reviewed.

1. Introduction

Leptoquarks are hypothetical bosons which couple to a lepton and a quark via a Yukawa coupling (denoted λ). In the Standard model, both quarks and leptons occur in left-handed $SU(2)$ doublets and right-handed $SU(2)$ singlets. The symmetry between quarks and leptons leads to the cancellation of triangle anomalies which make the SM renormalizable. Leptoquarks appear in theories[1] in which this symmetry is more fundamental.

Leptoquarks (LQs) are color triplets, which would be pair produced in either $q\bar{q}$ or gg interactions at $p\bar{p}$ or pp colliders. Because they carry electroweak charge, they would also be pair produced in e^+e^- or $\mu^+\mu^-$ collisions. Only standard model gauge couplings are involved in pair production; therefore the cross sections depend neither on the quark-lepton-LQ Yukawa coupling nor on the quark and lepton generations to which the leptoquark couples. In contrast, leptoquarks would be singly produced via the Yukawa coupling in a lepton-quark collision. Searches at electron-proton colliders are sensitive only to LQs which couple to electrons and the sensitivity to LQs which couple to second and third generation quarks is far below that of first-generation LQs. Leptoquarks are usually (but not always) assumed to be *generation diagonal*. Models in which LQs couple to more than one generation of quarks or leptons would induce flavor-changing neutral currents[2,3] or lepton flavor violation[2,4] respectively.

The model of Buchmüller, Rückl and Wyler[5] (BRW), in which leptoquarks couple to a single generation of SM fermions via chiral Yukawa couplings which are invariant under $SU(3) \times SU(2) \times U(1)$ is often used to classify possible leptoquark species. In the BRW model baryon and lepton numbers (B and L) are conserved; there exist ten possible leptoquark species characterized by the chirality of the coupling, the the spin ($J = 0$ or 1), the weak isospin ($T = 0, 1/2$, or 1), and the fermion number, $F = 3B + L = 0$ or 2 . Four of the species could have separate couplings to right- and left-handed leptons. A leptoquark which coupled first generation quarks to both left- and right-handed electrons would mediate $\pi \rightarrow e\nu$ decay[6]. The agreement of the measured decay rate with SM predictions motivates the conventional assumption that only one of the couplings can be nonzero. In the most commonly used notation[7] $F = 0$ scalar (S) and vector (V) species are denoted $S_{1/2}^L, S_{1/2}^R, \tilde{S}_{1/2}^L, V_0^L, V_0^R, \tilde{V}_0^R$ and V_1^L , while the $F = 2$ species are $S_0^L, S_0^R, \tilde{S}_0^R, S_1^L, V_{1/2}^L, V_{1/2}^R, \tilde{V}_{1/2}^L$. The sub- and superscripts indicate the lepton chirality and the weak isospin respectively. The species \tilde{S} and \tilde{V} differ by two units of hypercharge from S and V respectively. Partial widths for scalar and vector LQs with mass M_{LQ} are given by $\lambda^2 M_{LQ}/16\pi$ and $\lambda^2 M_{LQ}/24\pi$ respectively.

2. Leptoquark Searches the Tevatron

The Tevatron experiments have performed searches for first, second, and third generation

Gen.	β	M_{LQ} Limit (GeV)		Ref.
		Scalar	Vector	
1	1	225	246,345	D0[8,9,10]
	1/2	204	233,337	
1	1	213		CDF[12]
1	1	242		CDF+D0[13]
2	1	200	275,325	D0[14,15]
	1/2	180	260,310	
2	1	202		CDF[16,17]
	1/2	160		
	0	123	171,222	
1,2	0	98	200,298	D0[11]
3	0	94	148,209	D0[18]
3	1	99	170,217	CDF[19,17]
	0	148	199,250	

Table 1

Limits on leptoquarks from the Tevatron. The first two columns give the generation and β , the branching ratio to a charged lepton and a quark. The next two columns give the lower bounds on M_{LQ} (95% CL). Vector LQs limits are given for both low and high cross section models.

leptoquarks, including separate analyses for decays to charged leptons and to neutrinos. The results are summarized in table 1. Limits are more restrictive for LQs which decay to eq and μq than those decaying to νq . CDF has used their silicon vertex detector to tag b and c quarks[17] while D0 identifies b -jets by associated muons[18]. For scalar LQs, NLO cross section calculations[20] are used in limit setting. In vector LQ cross section calculations[21] (done at LO), the coupling of the LQ and gluon fields is model dependent and limits for several different models[8,19] are quoted.

3. Leptoquark Searches at HERA

At the HERA electron-proton collider, first-generation leptoquarks can be singly produced via fusion of the beam electron with valence quarks in the proton. Event by event, the electron-jet and neutrino-jet final states resulting from LQ production (or exchange of virtual LQs) are indistinguishable from Neutral and Charged Current Deep Inelastic Scattering (DIS).

If M_{LQ} is below the center of mass energy, ($\sqrt{s} = 318$ GeV) and the width of the LQ state is small, LQs would be produced as an s -channel resonance with cross section proportional to λ^2 . Leptoquark production and decay would give rise to a peak in the spectrum of lepton-jet invariant mass ($M_{\ell j}$), while the DIS background appears as a continuum. The lepton-jet invariant mass is related to the fraction x of the proton momentum carried by the interacting quark by $M_{\ell j}^2 = xs$. A LQ signal is distinguished from the DIS background by the angular distribution of the final-state leptons. Define θ^* as the angle between the incident electron and the final state lepton in the LQ rest frame and $y = 1 - \cos\theta^*$. The distribution of y for scalar LQ events is flat while vector LQs have a $1 - y^2$ distribution. In contrast, the NC-DIS background follows a $1/y^2$ distribution (for γ exchange). Both H1[22,23] and ZEUS[24] have searched for LQs by computing a λ -dependent likelihood for the 2-dimensional distributions of electron-jet and neutrino-jet events in $M_{\ell j}$ and y (or $\cos\theta^*$). This method is also sensitive to the changes in the observed ($M_{\ell j}, \cos\theta^*$) distribution resulting from u - and s -channel LQ diagrams with $M_{LQ} \gtrsim \sqrt{s}$. Example of the resulting limit curves are shown in Fig. 1. In table 2, the ZEUS lower limits on M_{LQ} for $\lambda = 0.1$ are shown. Both H1[25] and ZEUS[26] have also obtained limits for LQs with $M_{LQ} > \sqrt{s}$ by examining the Q^2 spectrum of NC-DIS-like events (Q^2 is the negative square of the 4-momentum transfer between the incident e and the hadronic system). Limits obtained in these analyses are consistent with those in the analyses described above. In addition ZEUS[27] and H1[23] have searched by LQs which couple to two different lepton generations, thereby inducing lepton flavor violation.

4. Leptoquark Searches at LEP

Three sorts of leptoquark searches have been performed at LEP. Leptoquarks with $M_{LQ} < \sqrt{s}/2$ would be pair produced via electroweak coupling. Using data with \sqrt{s} from 189 to 209 GeV OPAL[28] searched for scalar and vector LQs from all three generations, obtaining lower limits on M_{LQ} ranging from 72 to 102 GeV. Single LQ

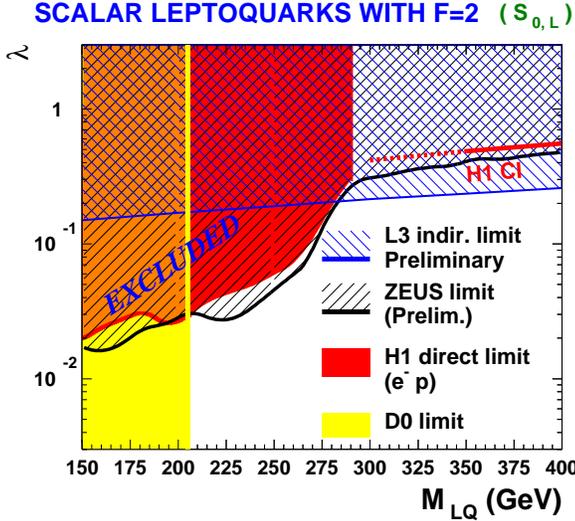


Figure 1. Limits on the S_0^L leptoquark in the (M_{LQ}, λ) plane. The excluded region lies above the curves for H1, L3, and ZEUS and to the left of the line for D0.

production can occur via the interaction of an electron with a radiated photon which resolves into $q\bar{q}$. Limits in the (M_{LQ}, λ) plane for various LQ species obtained by OPAL[29] range from 189 to 209 GeV for $\lambda = \sqrt{4\pi\alpha_{em}}$, where α_{em} is the fine structure constant. See [30] for DELPHI results. The most interesting LQ searches[31,32,33] performed at LEP look for indirect effects of t -channel ($F = 0$) or u -channel ($F = 2$) LQ exchange in the reaction $e^+e^- \rightarrow q\bar{q}$. L3 limits on λ vs. M_{LQ} for scalar LQs are shown in Fig. 2. Table 2 shows combined LEP limits[34] on LQs which couple to e and quarks of different generations. These limits were obtained using the cross section for $e^+e^- \rightarrow \text{hadrons}$ for \sqrt{s} between 130 and 207 GeV. For LQs which couple to ec and eb , the $c\bar{c}$ and $b\bar{b}$ fractions R_c and R_b , and the forward-backward asymmetries were also used.

5. Summary

For first generation leptoquarks, the Tevatron experiments have set limits on scalars (coupling to eq) of $M_{LQ} > 242$ GeV and corresponding vec-

species	LEP			ZEUS
	1 st	2 nd	3 rd	1 st
S_0^L	655	762	NA	274
S_0^R	520	625	NA	272
\tilde{S}_0^R	202	209	454	249
$S_{1/2}^L$	178	215	NA	281
$S_{1/2}^R$	232	185	-	281
$\tilde{S}_{1/2}^L$	-	-	226	270
S_1^L	361	408	1036	274
V_0^L	917	968	765	268
V_0^R	165	147	167	271
\tilde{V}_0^R	489	478	NA	279
$V_{1/2}^L$	303	165	208	248
$V_{1/2}^R$	227	466	499	273
$\tilde{V}_{1/2}^L$	176	101	NA	272
V_1^L	659	687	765	283

Table 2

Lower limits on M_{LQ} in GeV for different LQ species which couple to first-generation leptons. The first column gives the LQ species; the next three columns give the LEP combined limits for first, second, and third generation quarks with $\lambda = \sqrt{4\pi\alpha_{em}}$. A dash indicates that no limit could be set and NA indicates an LQ which couples only to top quarks, which would not be visible at LEP. The last column gives the ZEUS limits for $\lambda = 0.1$.

tor LQ limits in the range from 233 to 345 GeV, depending on model assumptions. The LEP experiments have set lower limits on M_{LQ} (which are approximately proportional to λ) which range from 165 to 917 GeV for $\lambda = \sqrt{4\pi\alpha_{em}} \sim 0.31$. The HERA experiments have set lower mass limits in the range of ~ 250 to 280 GeV for $\lambda = 0.1$. In addition, searches at the Tevatron and LEP have constrained LQs coupling to leptons and quarks of the second and third generations.

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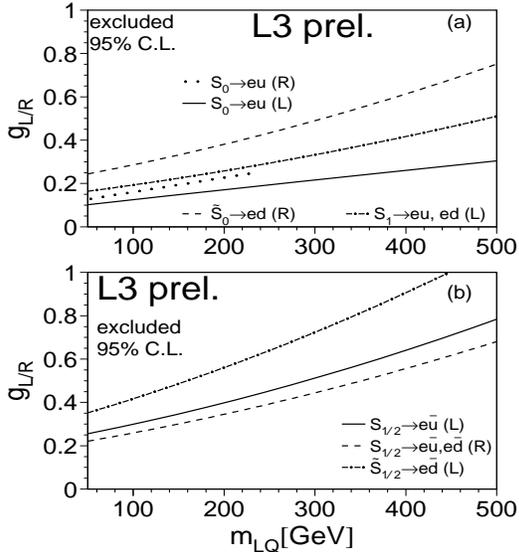


Figure 2. Scalar leptoquark limits in the (M_{LQ}, λ) plane from L3[31]. The area above the curves is excluded.

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