New Bounds on Leptoquarks

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(Received 5 April 1993)

We derive new bounds on scalar leptoquark couplings from K^0-$\bar{K}^0$, D^0-$\bar{D}^0$, and B^0-$\bar{B}^0$ mixing. Although leptoquarks contribute to these processes only at one loop, their contribution is large, due to the lack of Glashow-Iliopoulos-Maiani cancellation. Our bounds have two important features: (i) They bound g^4/M^2, in contrast to the hitherto known bounds on g^2/M^2, and are consequently stronger at high masses. (ii) The bound from D^0-$\bar{D}^0$ mixing is the first flavor changing neutral current bound in the up sector for chirally coupled leptoquarks, and is similar in strength to the K^0-$\bar{K}^0$ and B^0-$\bar{B}^0$ bounds. Together, these bounds strongly constrain any leptoquark that couples to left-handed quarks.

PACS numbers: 14.80.Gt, 12.15.Cc, 14.40.Aq, 14.40.Jz

In the last few years we have witnessed a renewed interest in low-lying leptoquarks. This has been stimulated on the one hand by the construction of the DESY *ep* collider HERA, which is an ideal machine for leptoquark searches, and on the other hand by nonstandard models which predict the existence of such particles. There are already several bounds on leptoquark masses and mixings from existing e^+e^- and $p\bar{p}$ machines [1]. These bounds can be summarized as follows: (i) The most stringent bounds arise when a leptoquark is allowed to couple to both left-handed (LH) and right-handed (RH) quarks. The pseudoscalar mesons π, K, and D can then decay leptonically without the "chiral suppression" of the standard model. To avoid these bounds, one usually demands that leptoquarks couple *chirally,* either to left-handed or to right-handed quarks, but not to both. (ii) The strongest bounds on *chirally* coupled leptoquarks arise from flavor changing neutral current (FCNC) processes in the lepton and the down sectors. It is therefore customary to demand that leptoquarks couple "diagonally" to these sectors; i.e., any leptoquark is allowed to couple only to a single lepton generation and a single down quark generation. (iii) The bounds are derived by considering *tree-level* leptoquark contributions to various processes. Therefore, once the masses are heavy relative to the available energies, the bounds apply to g^2/M^2. At present, the highest relevant energy is that of KEK's TRISTAN with $E \sim 60$ GeV, and "heavy masses" are $M \gtrsim 200$ GeV.

In this paper we wish to point out a new set of bounds. These arise from the one-loop contribution of the leptoquarks to neutral meson mixing. We first present these bounds for general scalar leptoquarks, without any restriction to "chiral" or "diagonal" couplings: Consider the coupling of a scalar leptoquark Φ to a particular lepton (or antilepton) l and to the down quarks d and s:

$$\mathcal{L} = \{\bar{l}[g_L^d P_L + g_R^d P_R]d + \bar{l}[g_L^s P_L + g_R^s P_R]s\}\Phi\,, \qquad (1)$$

where the indices on the coupling constants indicate the flavor and the chirality of the quark, and P_L and P_R are the LH and RH projection operators. The interaction (1) leads to a new contribution to K^0-$\bar{K}^0$ mixing via a loop of leptons and leptoquarks:

$$\Delta M_{12} = \frac{1}{192\pi^2 M_{LQ}^2}\,|\,(a_L^K)^2 + (a_R^K)^2 - (E_K + \tfrac{3}{2})a_L^K a_R^K|f_K^2 M_K\,, \qquad (2)$$

where $a_L^K = g_L^d(g_L^s)^*, a_R^K = g_R^d(g_R^s)^*$ and E_K is the ratio of $\langle\bar{K}^0|\bar{d}\gamma_5 s|0\rangle\langle 0|\bar{d}\gamma_5 s|K^0\rangle$ to $\langle\bar{K}^0|\bar{d}\gamma^\mu\gamma_5 s|0\rangle\langle 0|\bar{d}\gamma_\mu\gamma_5 s|K^0\rangle$. Demanding that the new contribution to ΔM_{12} does not exceed the measured value we get

$$\frac{1}{M_{LQ}^2}|(a_L^K)^2 + (a_R^K)^2 - (E_K + \tfrac{3}{2})a_L^K a_R^K| \le 5.2\times 10^{-10}\ \mathrm{GeV}^{-2}. \qquad (3)$$

There are a few important points we would like to impress on the reader: First, the contribution (2) to K^0-$\bar{K}^0$ mixing is particularly large, despite being one loop. This is because there is no Glashow-Iliopoulos-Maiani (GIM) mechanism for scalar leptoquarks and consequently no analog to the standard suppression factor m_c^2/M_W^2. The large contribution to the mixing translates, in Eq. (3), to a strong bound on the leptoquark coupling. Second, the contribution of the lepton-leptoquark loop is independent of the nature of the lepton (or antilepton). Corrections due to the lepton mass are small and were neglected. Finally, if there are several contributions with various leptons and leptoquarks running in the loop, the bound applies separately to each of them, since there is no GIM mechanism here and no significant cancellations are expected.

Repeating the same procedure for D^0-$\bar{D}^0$ and B^0-$\bar{B}^0$ mixing, we find

$$\frac{1}{M_{LQ}^2}|(a_L^D)^2 + (a_R^D)^2 - (E_D + \tfrac{3}{2})a_L^D a_R^D| \le 2.2\times 10^{-9}\ \mathrm{GeV}^{-2}, \qquad (4)$$

$$\frac{1}{M_{LQ}^2}|(a_L^B)^2 + (a_R^B)^2 - (E_B + \tfrac{3}{2})a_L^B a_R^B| \le 7.5\times 10^{-9}\ \mathrm{GeV}^{-2}, \qquad (5)$$

0031-9007/93/71(9)/1324(4)$06.00

TABLE I. 95% C.L. experimental bounds on the g_i and g_i' coupling. Masses are in GeV. Note that the first two bounds are quadratic in M, while the last two are linear. The FCNC bounds are presented with an explicit $\sin\theta_C$ factor. For e^+e^- scattering the scale Λ of a nonstandard physics was found in [4] to lie in the TeV range at 95% C.L. As a representative number we take $\Lambda = 5$ TeV.

	S	D	T
$\lvert g_1\rvert^2/M^2$	9.6×10^{-8} $\pi\to e\nu$[a]	5.0×10^{-7} e^+e^-[b]	5.0×10^{-7} e^+e^-[b]
$\lvert g_1'g_2'\rvert/M^2$	$4.5\times10^{-8}\sin\theta_C$ $K\to\pi\nu\bar\nu$[c]	$1.2\times10^{-7}\sin\theta_C$ $K_L\to ee$[d]	$8.9\times10^{-8}\sin\theta_C$ $K\to\pi\nu\bar\nu$[c]
$\lvert g_1'g_2'\rvert/M$	$1.0\times10^{-4}\sin\theta_C$ K^0-$\bar K^0$[e]	$1.0\times10^{-4}\sin\theta_C$ K^0-$\bar K^0$[e]	$9.3\times10^{-5}\sin\theta_C$ K^0-$\bar K^0$[e]
$\lvert g_1g_2\rvert/M$	$2.1\times10^{-4}\sin\theta_C$ D^0-$\bar D^0$[f]	$2.1\times10^{-4}\sin\theta_C$ D^0-$\bar D^0$[f]	$1.9\times10^{-4}\sin\theta_C$ D^0-$\bar D^0$[f]

[a]Reference [5].
[b]Reference [4].
[c]Reference [6].
[d]Reference [7].
[e]Reference [3].
[f]Reference [2].

where $a_L^D = g_L^u(g_L^c)^*, a_R^D = g_R^u(g_R^c)^*$ and $a_L^B = g_L^d(g_L^b)^*, a_R^B = g_R^d(g_R^b)^*$. Here we have used the Fermilab TPS bound on D^0-$\bar D^0$ mixing [2], which translates to $\Delta M \le 1.5\times10^{-4}$ eV at 95% C.L., and the Particle Data Group value [3] for B^0-$\bar B^0$ mixing, which translates to $\Delta M \le 5.0\times10^{-4}$ eV at 95% C.L.

The bounds (3)-(5) have two important features: First, they apply to g^4/M^2, in contrast to previous bounds which apply to g^2/M^2. Our bounds therefore dominate at high masses. As an example, consider bounds on FCNC in the down sector for chirally coupled leptoquarks: Previously, the strictest bounds were derived from $K\to\pi\nu\bar\nu$ and $K_L\to e^+e^-$ decays (see Table I). Now we also have the K-$\bar K$ bound, which is more stringent at masses of order 1 TeV.

The other important feature is the D^0-$\bar D^0$ mixing bound. This is the only *up* sector FCNC bound that applies to chirally coupled leptoquarks, and it has significant consequences: As mentioned above, all previous FCNC bounds for chirally coupled leptoquarks could be avoided by demanding that the leptoquarks couple diagonally to the lepton and down sectors. But now we need to demand the diagonality of the leptoquark couplings to the up sector as well. If the leptoquark couples to RH quarks, all "diagonality" demands in the lepton, down, and up sectors can be satisfied. But, if the leptoquark couples to LH quarks, Cabibbo-Kobayashi-Maskawa (CKM) mixing implies that we cannot diagonalize its couplings to the down and the up sectors simultaneously. We therefore find, in contrast to hitherto existing bounds, that FCNC bounds cannot be completely evaded when a leptoquark couples to LH quarks.

To display the power of our new bounds we shall now discuss leptoquarks that couple chirally to LH quarks, "as diagonally as possible" to the first generation of quarks and diagonally to a single (for definiteness, the first) generation of leptons. We will present the allowed regions in the coupling-constant–mass plane and see that large regions are excluded when our bounds are taken into account.

There are three types of scalar leptoquarks that couple to LH quarks: S, D, and T, which are a singlet, a doublet, and a triplet of $SU(2)_W$ and carry $Y = -\frac{1}{3}, -\frac{7}{6}$, and $-\frac{1}{3}$, respectively. In the following we will ignore possible mass splitting within each of the leptoquark multiplets and the possibility of mixing among the multiplets. The couplings to the fermions are given by

$$\begin{aligned}\mathcal{L}_S &= \sum_i (g_i \bar e^c u_L^i - g_i' \bar\nu^c d_L^i) S_{1/3}\,,\\ \mathcal{L}_D &= \sum_i \{g_i \bar e u_L^i D_{-5/3} + g_i' \bar e d_L^i D_{-2/3}\}\,,\\ \mathcal{L}_T &= \sum_i \{g_i \bar\nu^c u_L^i T_{-2/3} + (1/\sqrt{2})(g_i \bar e^c u_L^i + g_i' \bar\nu^c d_L^i) T_{1/3}\\ &\qquad + g_i \bar e^c d_L^i T_{4/3}\}\,,\end{aligned} \tag{6}$$

where the g_i and g_i' couplings are related by

$$g_i' = g_j V_{ji}\,, \tag{7}$$

with V the CKM mixing matrix. The relation (7) is the mathematical realization of the fact that we cannot fully diagonalize the couplings: If, for example, we choose to diagonalize the couplings to the down quark sector, demanding that g_2' and g_3' vanish, then the couplings to the up sector cannot be completely diagonal: g_2 and g_3 do not vanish, although they are suppressed by CKM factors. We will not make an *a priori* decision as to which sector should be diagonalized, but only demand that the g_i $(i=2,3)$ are CKM suppressed, that is,

$$g_i \lesssim g_1 V_{1i}\,. \tag{8}$$

Note that the same suppression will then apply to the g_i'

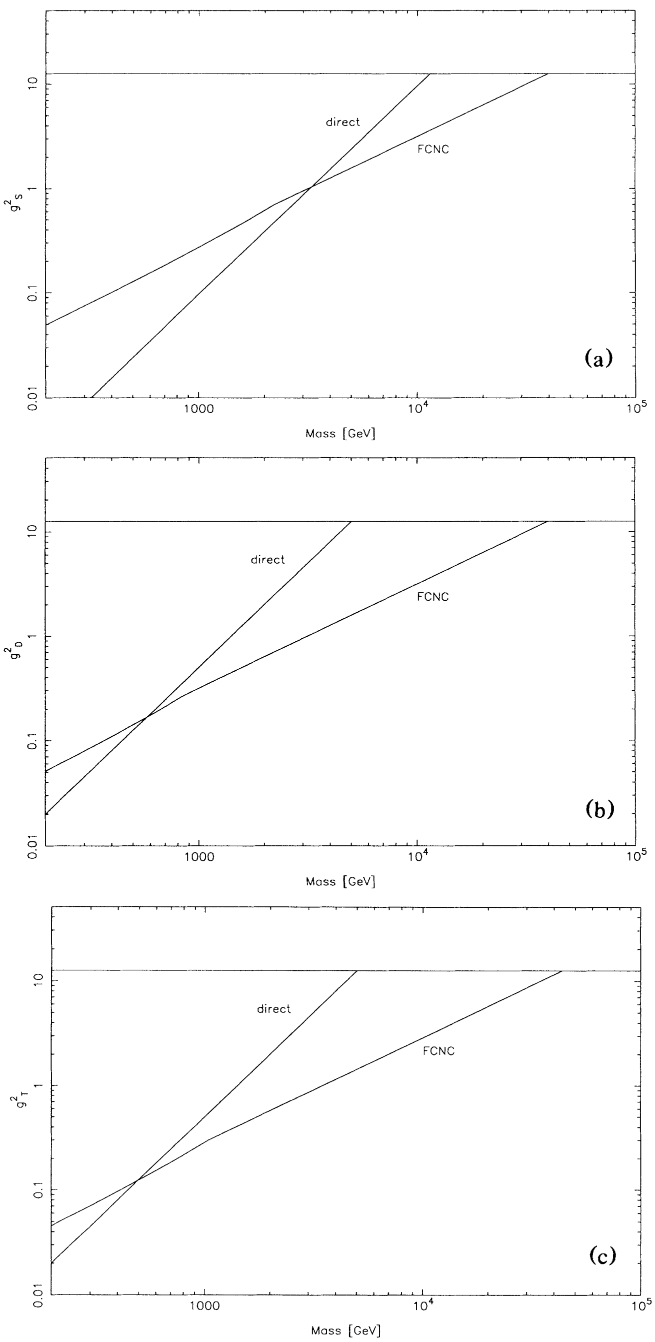

FIG. 1. (a)-(c) Upper bounds on the leptoquark coupling constant g as a function of its mass M, when the leptoquark couples to LH quarks of the first generation and to leptons of the first generation. (a)-(c) describe the bounds for the S, D, and T leptoquarks, respectively. We show the direct and FCNC bounds, as well as the 4π perturbative upper limit.

couplings, $g_i' \lesssim g_1' V_{1i}$, and that g_1 and g_1' are equal up to a small correction, to be neglected here.

In the following we ignore the third generation since its couplings are strongly suppressed (by V_{13}). We are then reduced to a two-generation picture, and parametrize our coupling constants as follows:

$$g_1 = g\cos\theta, \quad g_1' = g\cos(\theta+\theta_C)\,,$$
$$g_2 = g\sin\theta, \quad g_2' = g\sin(\theta+\theta_C)\,. \tag{9}$$

The g and θ parameters defined in Eq. (9) have the following interpretation: g is the coupling constant of the leptoquark to LH quarks, while θ determines the distribution of this coupling between the first and second generations. Since we choose to couple the leptoquark mainly to the first generation, $|\theta|$ is not larger than $\sim\theta_C$. The bounds derived from experimental data apply to the g_i and g_i' couplings, and are summarized in Table I.

We now translate the information of the table to bounds on g^2: The bound in the first row applies directly to g^2 (g and g_1 being equal up to a small correction which we neglect) and is quadratic in the leptoquark mass. This is the "classical" bound, which was known prior to this work.

The other bounds in the table are derived from FCNC processes. We rewrite them as

$$2|g_1' g_2'| = g^2|\sin 2(\theta+\theta_C)| \leq f(M)\,, \tag{10}$$

$$2|g_1 g_2| = g^2|\sin 2\theta| \leq g(M)\,, \tag{11}$$

where f and g are functions of the leptoquark mass M. Equation (10) summarizes the FCNC bounds in the down sector: At low leptoquark masses the rare K decay bound dominates and $f(M)$ is quadratic in the leptoquark mass, while in the high mass region the K^0-$\bar{K}^0$ bound dominates and $f(M)$ is linear. Equation (11) is the D^0-$\bar{D}^0$ bound, the only FCNC bound of the up sector. $g(M)$ is linear in the leptoquark mass. One could evade the FCNC bounds in one of the sectors by choosing $\theta = -\theta_C$ or $\theta = 0$, but it is impossible to evade the bounds in both sectors simultaneously. Every θ will lead to a bound on g^2. The weakest possible bound corresponds to a compromise between the two sectors, that is to $\theta(M)$, which is between $-\theta_C$ and 0:

$$\sin 2\theta(M) = -\frac{\sin 2\theta_C}{\sqrt{(\sin 2\theta_C)^2 + [\cos 2\theta_C + f(M)/g(M)]^2}}\,. \tag{12}$$

Then the combined effect of the FCNC constraints in the up and the down sectors gives the bound

$$g^2 \leq g^2_{\rm max} = f(M)/\sin 2[\theta(M)+\theta_C] = g(M)/\sin 2\theta(M)\,. \tag{13}$$

Note that in the high mass region $\theta(M)$ is M independent [$\sin 2\theta(M) \approx -0.3$] and $g^2_{\rm max}$ is linear in M. The new FCNC bound therefore becomes stronger than the classical quadratic bound at high leptoquark masses, and it excludes new regions in the coupling-constant–mass plane. The classical bound and the new FCNC combined bound are shown in Figs. 1(a)-1(c) for the various leptoquarks.

Summarizing, we have found new FCNC bounds on leptoquark couplings by examining their one-loop contributions to neutral meson mixing. The new bounds are particularly powerful for leptoquarks that couple to left-handed quarks: In this case, since the CKM mixing implies that FCNC cannot be avoided in both the up and the down sectors, our K^0-$\bar{K}^0$ and D^0-$\bar{D}^0$ bounds combine to bound the flavor *conserving* coupling constant. This bound is shown in Figs. 1(a)–1(c), and it excludes large regions in the coupling-constant–mass plane. Although these regions lie beyond HERA's kinematical limit, they are significant for virtual leptoquark searches in HERA, and for searches in the Superconducting Super Collider and the CERN Large Hadron Collider.

I thank Neil Marcus for helpful conversations.

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