

Comprehensive study of leptoquark bounds

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We make a comprehensive study of indirect bounds on scalar leptoquarks that couple chirally and diagonally to the first generation by examining available data from low-energy experiments as well as from high energy e^+e^- and $p\bar{p}$ accelerators. The strongest bounds turn out to arise from low-energy data: For leptoquarks that couple to right-handed quarks, the most stringent bound comes from atomic parity violation. For leptoquarks that couple to left-handed quarks, there are two mass regions: At low masses the bounds arise from atomic parity violation or from universality in leptonic π decays. At masses above a few hundred GeV's the dominant bounds come from the flavor-changing neutral current (FCNC) processes that are unavoidable in these leptoquarks: The FCNC bound of the up sector, that arises from $D^0-\bar{D}^0$ mixing, combines with the FCNC bounds from the down sector, that arise from rare K decays and $K^0-\bar{K}^0$ mixing, to a bound on the flavor *conserving* coupling to the first generation. The bounds restrict leptoquarks that couple with electromagnetic strength to lie above 600 or 630 GeV for leptoquarks that couple to right-handed quarks, and above 1040, 440, and 750 GeV for the $SU(2)_W$ scalar, doublet, and triplet leptoquarks that couple to left-handed quarks. These bounds are considerably stronger than the first results from the direct searches at the DESY ep collider HERA. Our bounds also already exclude large regions in the parameter space that could be examined by various methods proposed for indirect leptoquark searches.

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I. INTRODUCTION

The original motivation for this research was to compare the oncoming results from the direct leptoquark search at the DESY ep collider HERA [1] with indirect bounds that are available from various low-energy experiments and from e^+e^- and $p\bar{p}$ colliders. A previous study [2] of such indirect bounds was completed in 1986, and we sought to update it and improve on it in various aspects. First, we considered all possible scalar leptoquarks while the work in Ref. [2] dealt only with the superstring inspired E_6 leptoquark, called S in our paper. Second, there are new experimental results which enable us to derive considerably stronger bounds. In particular, there has been a lot of progress in both experimental measurements and theoretical calculations for atomic parity violation and universality in leptonic π decays. Third, we take into account bounds from $K^0-\bar{K}^0$ and $D^0-\bar{D}^0$ mixing. The significance of these bounds was pointed out only recently [3]. Finally, we extract, for each leptoquark, only the *utterly unavoidable* bound on its mass and its coupling to the first generation. Obviously, these are the relevant bounds for the direct searches in HERA, as well as for other direct and indirect searches.

Our final bounds are presented in Fig. 1, where the mass range extends to the multi-TeV range. This figure can be used to examine the feasibility of methods proposed for leptoquark searches in various machines. The bounds can also be read from Tables I, II, and VII. The tables are convenient to use since they give the lower bound on the mass as a simple function of the coupling constant, but for some leptoquarks the bounds in the tables are somewhat weaker than the full bounds present-

ed in the figures. In Fig. 2, we also compare our bounds to the first HERA results.

Since we are interested in the "utterly unavoidable" bounds, let us set the stage for them by reviewing the means for circumventing other bounds. Basically, there are three requirements that leptoquarks should obey in order to evade some of the strongest bounds on their parameters: They should *not* couple to diquarks, and they should couple chirally and diagonally. We will now explain in some detail the meaning of these conditions.

(i) Diquark couplings are forbidden since they, together with the lepton-quark couplings lead to nucleon decay. The bound on the leptoquark mass is then extremely strong, of the order of the scale of grand-unified theories.

(ii) When we say that a leptoquark couples chirally, we mean that it couples *either* to left-handed (LH) *or* to right-handed (RH) quarks, but not to both. A nonchiral leptoquark induces the following four-Fermi interaction:

$$\mathcal{L}_{\text{eff}} = \frac{g_L g_R}{2M^2} \bar{u}_R d_L \bar{e}_R \nu_L, \quad (1.1)$$

where M is the leptoquark mass and g_L and g_R are its couplings to LH and RH quarks, respectively. The above interaction contributes to $\pi \rightarrow e\nu$ decay and, in contrast to the standard model interaction, it is not chiral and its amplitude is not helicity suppressed. The amplitude is therefore enhanced by m_π/m_e relative to the standard model amplitude and, in addition, it is possible to show that there is further enhancement by $m_\pi/(m_u + m_d)$ [4]. The enhanced effect of the interaction (1.1) leads to unacceptable deviations from lepton universality in π decays, unless one strongly constrains the leptoquark parameters with the 95% C.L. bound as strong as

$$M^2/|g_L g_R| \geq (100 \text{ TeV})^2 .$$

The chirality requirement enables us to circumvent this bound.

(iii) Leptoquarks couplings are called “diagonal” when the leptoquark couples to a single leptonic generation and to a single quark generation. If the leptoquarks couple nondiagonally they induce flavor-changing neutral current (FCNC) processes in both the leptonic sector and the quark sector, leading to strict bounds on the leptoquark parameters [2,5]. To avoid these bounds we impose diagonality of the couplings. However, we recently pointed out [3] that diagonality is not really possible for leptoquarks that couple to left-handed quarks. The fact that the Cabibbo-Kobayashi-Maskawa (CKM) matrix [6] is not trivial implies that one cannot diagonalize the leptoquark interactions simultaneously in the up and the down quark sectors. For example, if the couplings to the up sector are diagonal, and the leptoquark couples only to the first generation up quark, then the couplings in the down sector are not diagonal: The leptoquark couples “mainly” to the down quark, but there is also some coupling to the strange quark (suppressed by $\sin\theta_C$) and some coupling to the bottom quark (suppressed by V_{13} , where V is the CKM matrix). Similarly, if the leptoquark couples diagonally to the down quark, then its couplings to the up quark sector are *almost* diagonal, but not strictly so. In the following, we assume approximate diagonality of the leptoquark couplings to LH quarks: the leptoquarks couple mainly to the first generation, with their couplings to the second and third generations suppressed by $\mathcal{O}(\sin\theta_C)$ and $\mathcal{O}(|V_{13}|+|V_{12}V_{23}|)$, respectively. Approximate diagonality softens the FCNC bounds, but does not avoid them completely. In Sec. VI we shall analyze this problem in detail, and show that the FCNC bounds from the two sectors combine to give a significant and unavoidable bound on the *flavor conserving* coupling of the leptoquark to the first generation.

We should stress that the unavoidable bounds, which are the subject of this paper, are *independent* of the above assumptions on the leptoquarks couplings. These assumptions are just a matter of convenience: With them, avoidable bounds are circumvented and the discussion of the unavoidable bounds simplifies.

In addition to the assumptions on the leptoquark couplings, we make two “working assumptions”: First, we assume that at most one leptoquark multiplet exists. Second, we ignore mass splitting within a leptoquark multiplet. With these assumptions the presentation of bounds simplifies considerably, as there are only two parameters: a single coupling and a single mass. In Appendix B we discuss the modification of our bounds when the working assumptions are dropped.

The rest of the paper is organized as follows. In the following section we present the leptoquarks and their interactions and introduce notation, then we turn to bounds. In Sec. III we quote the bounds on the leptoquark parameters from the direct searches at the CERN Large Electron-Positron Collider (LEP), UA2 and the Collider Detector at Fermilab (CDF). Sections IV–VI discuss the strongest indirect bounds we find. Section IV

deals with atomic parity violation, Sec. V with universality in leptonic π decays, and Sec. VI with FCNC bounds. Section VIA is introductory, Sec. VIB discusses rare K decay bounds, and Sec. VIC describes neutral meson mixings bounds. In Sec. VID we combine the FCNC bounds from the two quark sectors to a bound on the flavor conserving coupling to the first generation. Section VII is a summary of our results. We have relegated to Appendix A several bounds that are weaker than those of Secs. IV–VI. These include bounds from eD scattering, $p\bar{p}$ scattering to e^+e^- , hadronic forward-backward asymmetry in e^+e^- accelerators, and universality in leptonic K decays. In Appendix B we consider the modification of our bounds when the “working assumptions” are dropped.

II. THE SCALAR LEPTOQUARKS AND THEIR INTERACTIONS

The list of all possible scalar leptoquarks [7] includes the S and the \tilde{S} leptoquarks in the $(0)_{1/3}$ and $(0)_{4/3}$ representations of $SU(2)_W \times U(1)_Y$, the D and \tilde{D} leptoquarks in the $(\frac{1}{2})_{-7/6}$ and $(\frac{1}{2})_{-1/6}$ representations, and the T leptoquark in the $(1)_{1/3}$ representation. Some of these leptoquarks are forced to couple chirally by their $SU(2)_W$ representations: \tilde{S} and \tilde{D} can couple only to RH quarks, T only to LH quarks. The other leptoquarks, S and D , can couple either to RH or to LH quarks. We will call these leptoquarks S_R and D_R when they couple to RH quarks and S_L and D_L when they couple to LH quarks. Note that our subscripts R and L are determined by the quark helicities, in contrast to the notation in Ref. [7], which is fixed by the lepton helicity. As a result, our notation for the subscript on the D leptoquark is opposite to the one of Ref. [7].

The Yukawa interactions of the leptoquarks that couple to RH quarks are given by

$$\begin{aligned} \mathcal{L}_{S_R} &= g \bar{e}^c u_R S_R^{(1/3)} , \\ \mathcal{L}_{\tilde{S}} &= g \bar{e}^c d_R \tilde{S}^{(4/3)} , \\ \mathcal{L}_{D_R} &= g (\bar{e} u_R D_R^{(-5/3)} + \bar{\nu} u_R D_R^{(-2/3)}) , \\ \mathcal{L}_{\tilde{D}} &= g (\bar{e} d_R \tilde{D}^{(-2/3)} + \bar{\nu} d_R \tilde{D}^{(1/3)}) , \end{aligned} \tag{2.1}$$

where the superscripts on the leptoquark fields indicate their electromagnetic charge.

The Yukawa couplings of the leptoquarks that couple to LH quarks are more complicated. Here we need to introduce two sets of couplings: g_i is the coupling to the i th up-quark generation, g'_i is the coupling to the i th down-quark generation and they are related by a CKM rotation: $g'_i = g_j V_{ji}$, with V the CKM mixing matrix¹

¹The normalization of the couplings of the T leptoquark is the one used in Ref. [7]. The T couplings we used in Ref. [3] are larger by $\sqrt{2}$ than the couplings we use here.

$$\begin{aligned}
\mathcal{L}_{S_L} &= \sum_i (g_i \bar{e}^c u_L^i - g_i' \bar{\nu}^c d_L^i) S_L^{(1/3)}, \\
\mathcal{L}_{D_L} &= \sum_i (g_i \bar{e} u_L^i D_L^{(-5/3)} + g_i' \bar{e} d_L^i D_L^{(-2/3)}), \\
\mathcal{L}_T &= \sum_i [\sqrt{2} g_i \bar{\nu}^c u_L^i T^{(-2/3)} + (g_i \bar{e}^c u_L^i + g_i' \bar{\nu}^c d_L^i) T^{(1/3)} \\
&\quad + \sqrt{2} g_i' \bar{e}^c d_L^i T^{(4/3)}].
\end{aligned} \tag{2.2}$$

In order to present our bounds we define the overall strength of the Yukawa couplings to be g , with

$$g = \left[\sum_i |g_i|^2 \right]^{1/2}, \tag{2.3}$$

and give our final results as bounds in the g - M plane. Note that since we assume that the leptoquarks couple mainly to the first generation, the second and third generation couplings are suppressed by $O(\sin\theta_C)$ and $O(|V_{13}| + |V_{12}V_{23}|)$. The first generation couplings are then equal to g to a very good approximation (up to 2–3%), and in the following we will often ignore the differences between g , g_1 , and g_1' .

For convenience, we also introduce the parameters η_I , with I running over all leptoquark multiplets: $I = S_L, S_R, \tilde{S}, D_L, D_R, \tilde{D}$, and T . η_I gets the value 1 when we consider a theory with the leptoquark I , and otherwise it vanishes.

III. BOUNDS FROM DIRECT SEARCHES AT LEP AND TEVATRON

The LEP experiments searched for leptoquark pair production in Z decays. No evidence for such a decay mode was found and consequently LEP set a lower bound on the leptoquark mass: $M \gtrsim M_Z/2$ [8].

UA2 [9] and CDF [10] searched for leptoquark pairs produced via an intermediate gluon. In contrast to LEP, where one can search for all types of leptoquark pair events, namely, (i) events with both leptoquarks decaying to a charged lepton and a jet, (ii) events with one leptoquark decaying to a charged lepton and a jet and the other to a neutrino and a jet, and (iii) events with both leptoquarks decaying to a neutrino and a jet, the UA2 experiment did not search for the last type of events, and CDF did not search for the last two types of events. Consequently, the bounds from these experiments depend on b , the branching ratio of the decay of the leptoquark to a

TABLE I. Atomic parity violation 95% C.L. lower bounds on the ratio M/g , in GeV. We present the bounds in three equivalent ways in order to simplify the comparison to the various notations used in other leptoquark papers. $M_{4\pi}$ is the lower bound on the leptoquark mass when the coupling becomes non-perturbative $g^2=4\pi$, M_1 is the bound when the coupling is 1 and it is thus the bound on M/g and M_e is the bound when the coupling is equal to the electromagnetic coupling $g=e$.

	S_L	S_R	\tilde{S}	D_L	D_R	\tilde{D}	T
$M_{4\pi}$	3600	7000	7400	5200	7000	7400	6400
M_1	1000	2000	2100	1500	2000	2100	1800
M_e	305	600	630	440	600	630	550

charged lepton and a quark: If $b = \frac{1}{2}$ CDF bounds the leptoquark mass to lie above 80 GeV, and if $b = 1$ to lie above 113 GeV [10]. Studying the interactions (2.1) and (2.2), one sees that S_L has $b = \frac{1}{2}$ and its mass is therefore constrained to lie above 80 GeV. All the other leptoquark multiplets contain at least one component with $b = 1$. Under our working assumption of no mass splittings within a leptoquark multiplet, we find that all the leptoquarks, with the exception of S_L , are heavier than 113 GeV.

IV. ATOMIC PARITY VIOLATION

Measurements of atomic parity violation have not previously been used to set bounds on leptoquarks, although it was pointed out in Ref. [11] that such bounds could be very significant. In fact, recent improvement on measurements of atomic parity violation in cesium as well as improved theoretical calculations turn out to lead to very strong bounds. The relevant quantity is the cesium “weak charge” defined by

$$Q_W = -2[C_{1u}(2Z+N) + C_{1d}(2N+Z)], \tag{4.1}$$

with C_{1u} and C_{1d} defined, e.g., in Ref. [12] and with $Z = 55$ and $N \simeq 77.9$ for cesium. The latest experimental result [13] and the standard model estimate [14] for Q_W are

$$\begin{aligned}
Q_W^{\text{expt}} &= -71.04 \pm 1.81, \\
Q_W^{\text{SM}} &= -73.12 \pm 0.09.
\end{aligned} \tag{4.2}$$

In a theory with a leptoquark, there is an additional contribution to Q_W , given by

$$\begin{aligned}
\Delta Q_W^{\text{LQ}} &= -2 \left[\frac{g/M}{g_W/M_W} \right]^2 \\
&\times [(2Z+N)(-\eta_{S_L} + \eta_{S_R} - \eta_{D_L} + \eta_{D_R} - \eta_T) \\
&\quad + (Z+2N)(\eta_{\tilde{S}} - \eta_{D_L} + \eta_{\tilde{D}} - 2\eta_T)].
\end{aligned} \tag{4.3}$$

Here g and M are the coupling and mass of the leptoquarks and g_W and M_W are the coupling and mass of the W boson. The close agreement between the experimental Q_W value and the standard model estimate [see Eq. (4.2)] leads to strong bounds on g/M . These are summarized in Table I.

The bounds we will discuss in the following sections apply only to the leptoquarks that couple to LH quarks. Table I therefore contains our final bounds on the leptoquarks that couple to RH quarks (S_R, \tilde{S}, D_R , and \tilde{D}) and these can be summarized by $M/g \gtrsim 2$ TeV.

V. BOUNDS FROM UNIVERSALITY IN LEPTONIC π DECAYS

A remarkable progress has been achieved in both experimental and theoretical research of leptonic π decays. There have been two new experiments, one at TRIUMF [15], the other at PSI [16]. Combining their re-

TABLE II. 95% C.L. bounds on the ratio M/g , in GeV, from universality in leptonic π decays.

	S_L	T
$M_{4\pi}$	12 000	6400
M_1	3 400	1800
M_e	1 040	540

sults we find

$$R^{\text{expt}} = (1.2310 \pm 0.0037) \times 10^{-4}, \quad (5.1)$$

where

$$R = B(\pi \rightarrow e\nu) / B(\pi \rightarrow \mu\nu).$$

The theoretical standard model calculation by Marciانو and Sirlin has been updated [17] and it now yields

$$R^{\text{SM}} = (1.2352 \pm 0.0005) \times 10^{-4}. \quad (5.2)$$

The theoretical prediction in a theory with a leptoquark is

$$R^{\text{LQ}} = R^{\text{SM}} \left[1 + \left(\frac{g/M}{g_W/M_W} \right)^2 (\eta_{S_L} - \eta_T) \right]^2. \quad (5.3)$$

Equations (5.1)–(5.3) lead to the bounds of Table II. Note that for S_L the bound on M/g of the leptoquark is considerably stronger than the bound from atomic parity violation, while for the T leptoquark the two bounds (universality in leptonic π decays and atomic parity violation) are essentially equal.

VI. BOUNDS FROM FCNC PROCESSES

A. Introduction to FCNC bounds

As mentioned above, leptoquarks that couple to LH quarks have two sets of coupling constants, g_i is the coupling to the uplike quark of the i th generation and g'_i are the couplings to the downlike quarks. The g_i and g'_i are related through a CKM rotation. Since we consider leptoquarks that couple mainly to the first generation, the third generation couplings are so suppressed that they have actually no effect. We therefore ignore them and reduce to a two-generation picture so that

$$\begin{aligned} g_1 &= g \cos\theta \quad \text{and} \quad g_2 = -g \sin\theta, \\ g'_1 &= g \cos(\theta_C - \theta) \quad \text{and} \quad g'_2 = g \sin(\theta_C - \theta). \end{aligned} \quad (6.1)$$

The angle θ describes the deviation from diagonality in the up sector, while $(\theta_C - \theta)$ describes the deviation from diagonality in the down sector. θ therefore determines the division of the FCNC problems between the two quark sectors. Note that we do not consider the possibility of a nontrivial phase between g_1 and g_2 . Such a phase leads to very severe bounds, since the leptoquarks will contribute to the ϵ parameter of K^0 - \bar{K}^0 mixing [4]. These bounds are stronger by $\sqrt{(\sin 2\alpha)/(2\sqrt{2}\epsilon)}$ than the K^0 - \bar{K}^0 mixing bounds of Table V, where α is the phase. Since we are interested only in the *unavoidable* bounds on the leptoquark couplings, we discard the case of complex couplings.

TABLE III. $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay 95% C.L. bounds on the coupling constant combination $g'_1 g'_2$. The bounds are given as a function of the leptoquark mass M , with M in GeV.

	S_L	T
$ g'_1 g'_2 \leq$	$1.86 \times 10^{-8} \sin\theta_C M^2$	$1.86 \times 10^{-8} \sin\theta_C M^2$

The FCNC bounds from the up sector apply to the coupling combination $|g_1 g_2|$ and the FCNC bounds from the down sector to the combination $|g'_1 g'_2|$. In the following sections we give the upper bounds on these coupling constants combinations as a function of the leptoquark mass M , and in Sec. VID we combine these bounds into bounds on g .

B. Bounds from K decays

Leptoquarks induce the rare K decays $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow e^+ e^-$. $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay is induced by the S_L and T leptoquarks via the effective interaction

$$\mathcal{L}_{\text{eff}} = \frac{g'_1 g'_2}{2M^2} \bar{s} \gamma_\mu P_L d \bar{\nu} \gamma^\mu P_L \nu (\eta_{S_L} + \eta_T), \quad (6.2)$$

where $P_L = (1 - \gamma_5)/2$ is the LH projection operator. The 95% C.L. experimental bound on the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay rate [18] is

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \leq 6.8 \times 10^{-9}. \quad (6.3)$$

Comparing the branching ratio induced by Eqs. (6.2) and (6.3) leads to the bounds of Table III.

$K_L \rightarrow e^+ e^-$ decay is induced by the D_L and T leptoquarks via the effective interaction

$$\mathcal{L}_{\text{eff}} = \frac{g'_1 g'_2}{2M^2} \bar{s} \gamma_\mu P_L d (2\eta_T \bar{e} \gamma^\mu P_L e - \eta_{D_L} \bar{e} \gamma^\mu P_R e), \quad (6.4)$$

where P_L and P_R are the LH and RH projection operators, respectively. The 95% C.L. experimental bound on the $K_L \rightarrow e^+ e^-$ decay rate [19] is

$$B(K_L \rightarrow e^+ e^-) \leq 5.3 \times 10^{-11}. \quad (6.5)$$

Comparing the branching ratio induced by Eq. (6.4) with Eq. (6.5) leads to the bounds of Table IV.

C. Bounds from neutral meson mixings

The S_L , D_L , and T leptoquarks induce new contributions to K^0 - \bar{K}^0 and D^0 - \bar{D}^0 mixing via loops of leptons and leptoquarks. One could, at first thought, discard the bounds from neutral meson mixings as unimportant, since they arise only at one loop, in contrast to other leptoquark bounds that arise already at tree level. However, such an approach is mistaken. After all, K^0 - \bar{K}^0 and

TABLE IV. $K_L \rightarrow e^+ e^-$ decay 95% C.L. bounds on the coupling constant combination $g'_1 g'_2$. The bounds are given as a function of the leptoquark mass M , with M in GeV.

	D_L	T
$g'_1 g'_2 \leq$	$2.92 \times 10^{-8} \sin\theta_C M^2$	$1.46 \times 10^{-8} \sin\theta_C M^2$

TABLE V. $K^0\text{-}\bar{K}^0$ mixing bounds on the coupling constant combination $g'_1g'_2$. The bounds are given as a function of the leptoquark mass M , with M in GeV.

	S_L	D_L	T
$ g'_1g'_2 \leq$	$1.25 \times 10^{-4} \sin\theta_C M$	$1.25 \times 10^{-4} \sin\theta_C M$	$5.58 \times 10^{-5} \sin\theta_C M$

$D^0\text{-}\bar{D}^0$ mixing arise in the standard model too only at one loop. Moreover, the Glashow-Iliopoulos-Maiani (GIM) mechanism of the standard model leads to a suppression of, e.g., $K^0\text{-}\bar{K}^0$ mixing by $(m_c/M_W)^2$, while for the leptoquarks contribution there is no suppression of this kind. We should therefore expect neutral meson mixing to give us significant bounds on the leptoquarks parameters.

The leptoquarks contribution to $K^0\text{-}\bar{K}^0$ and $D^0\text{-}\bar{D}^0$ mixing are given by

$$\Delta M_{12}^K = \frac{1}{192\pi^2 M^2} (g'_1g'_2)^2 f_K^2 B_K M_K (\eta_{S_L} + \eta_{D_L} + 5\eta_T),$$

$$\Delta M_{12}^D = \frac{1}{192\pi^2 M^2} (g_1g_2)^2 f_D^2 B_D M_D (\eta_{S_L} + \eta_{D_L} + 5\eta_T). \quad (6.6)$$

Demanding that the leptoquark contribution to $K^0\text{-}\bar{K}^0$ mixing does not exceed the measured value of $\Delta M_{12}^K = 3.52 \times 10^{-6}$ eV [12], and that the leptoquark contribution to $D^0\text{-}\bar{D}^0$ mixing does not exceed the 95% C.L. experimental bound $\Delta M_{12}^D \leq 1.5 \times 10^{-4}$ eV [20] we are led to the bounds of Tables V and VI. The values of the B parameters we used are $B_K = 0.7$ [21] and $B_D = 1.0$, and for the D decay constant we took $f_D = 0.25$ GeV.

Note that the $K^0\text{-}\bar{K}^0$ and $D^0\text{-}\bar{D}^0$ mixing bounds are different from all previous bounds: The bounds from atomic parity violation, universality in leptonic π decays, and rare K decays all apply to g/M or $g'_1g'_2/M^2$, so $g \propto M$. In contrast, the neutral meson mixing bounds apply to $g'_1g'_2/M$ and g_1g_2/M , so $g \propto \sqrt{M}$. This difference is due to the fact that all previous bounds arise from tree-level leptoquark contributions, while $K^0\text{-}\bar{K}^0$ and $D^0\text{-}\bar{D}^0$ mixing arise at the one-loop level, and this turns out to be advantageous: The bounds from neutral meson mixings, because of their different functional dependence on the couplings and mass, *always* become the dominant bounds at the high mass region.

D. Combining the FCNC bounds to a bound on g

In this section we will combine the FCNC bounds from the two quark sectors to an *unavoidable bound* on the overall coupling g . Since g is equal to a very good approximation to g_1 and g'_1 , this means that the FCNC bounds combine to a bound on the *flavor conserving* coupling of the leptoquarks to the first generation.

We summarize the FCNC bounds in the following manner:

$$f_u(M) \geq |g_1g_2| = g^2 \sin(2|\theta|)/2,$$

$$f_d(M) \geq |g'_1g'_2| = g^2 \sin(2|\theta_C - \theta|)/2, \quad (6.7)$$

where $f_u(M)$ and $f_d(M)$ are the strongest FCNC bounds of the up and down quark sectors, respectively, and can be read from Tables III–VI. Equations (6.7) make it clear that *any* angle θ leads to bounds on g^2 . We are interested in the unavoidable bound on the coupling and we therefore look for the “best” angle θ , i.e., the one that leads to the softest bounds on g^2 . This angle is given by simultaneously saturating the two inequalities in (6.7), so that

$$\frac{f_u(M)}{f_d(M)} = \left| \frac{\sin 2\theta}{\sin 2(\theta_C - \theta)} \right|. \quad (6.8)$$

Solving Eq. (6.8) for the “best” angle θ ,

$$\tan(2\theta^{\text{best}}) = \frac{\sin 2\theta_C}{f_d/f_u + \cos 2\theta_C}, \quad (6.9)$$

and substituting this angle into either of the two inequalities of (6.7), we get the *unavoidable* FCNC bound on the overall coupling g :

$$g^2(M) \leq 2f_u(M)/\sin 2[\theta^{\text{best}}(M)]. \quad (6.10)$$

Again, we wish to stress [3] that the FCNC bound always become the most stringent bound in the high mass region. To see that, note that in this region both f_u and f_d are linear in the leptoquark mass: f_u is the $D^0\text{-}\bar{D}^0$ mixing bound and is therefore always linear in M . f_d is the strongest of the rare K decay bounds and the $K^0\text{-}\bar{K}^0$ mixing bound. Since the rare K decays bounds on $g'_1g'_2$ are quadratic in M while the $K^0\text{-}\bar{K}^0$ mixing bound is linear, the latter will dominate at high masses. Therefore, at high masses, the ratio f_d/f_u is independent of the leptoquark mass; consequently, the “best” angle θ is also M independent [see Eq. (6.9)], and the bound on g^2 is linear in M [see Eq. (6.10)]. In contrast, the atomic parity violation and universality in leptonic π decay bounds on g^2 are quadratic in M . The combined FCNC bound will therefore always dominate at high enough masses. Indeed, we find that the FCNC bound dominates above 3600 GeV in the case of S_L , but already above 570 and 390 GeV in the cases of D_L and T , respectively.

In Table VII we list the combined FCNC bound from $D^0\text{-}\bar{D}^0$ and $K^0\text{-}\bar{K}^0$ mixing. This is a true FCNC bound,

TABLE VI. $D^0\text{-}\bar{D}^0$ mixing 95% C.L. bounds on the coupling constant combination g_1g_2 . The bounds are given as a function of the leptoquark mass M , with M in GeV.

	S_L	D_L	T
$ g_1g_2 \leq$	$2.24 \times 10^{-4} \sin\theta_C M$	$2.24 \times 10^{-4} \sin\theta_C M$	$1.00 \times 10^{-4} \sin\theta_C M$

although in the low mass region there are stronger FCNC bounds combined from D^0 - \bar{D}^0 mixing and rare K decays.

VII. SUMMARY

We made a comprehensive survey of the bounds on scalar leptoquarks couplings to the first generation. We have discarded bounds that can be avoided, and concentrated only on those bounds that are completely inescapable. We found that the most stringent bounds arise from low-energy data: Atomic parity violation, universality in leptonic π decays and FCNC processes ($K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay, $K_L \rightarrow e^+ e^-$ decay, and K^0 - \bar{K}^0 and D^0 - \bar{D}^0 mixing).

Our final bounds can be summarized in a few different ways: Figures 1(a) and 1(b) show the overall bound on g as a function of M for all the leptoquarks. Figure 1(a) describes the bounds on the leptoquarks that couple to RH quarks; these come from atomic parity violation and are also given in Table I. Figure 1(b) describes the bounds on the leptoquarks that couple to the LH quarks, and here one distinguishes three mass regions for each of the leptoquarks: In the low mass region the dominant bound

arises from atomic parity violation or from universality in leptonic π decays and it depends on g/M . In the high mass region the most stringent bound is the FCNC bound derived by combining the K^0 - \bar{K}^0 and D^0 - \bar{D}^0 mixing bounds, and it depends on g^2/M . There is also an intermediate mass region, where the strongest bound is the FCNC bound combined from rare K decays and D^0 - \bar{D}^0 mixing. The functional dependence of this bound on g and M is more complicated. Note that the FCNC bounds exclude large new regions in the leptoquark parameter space, and for D_L and T these bounds become dominant already at 570 and 390 GeV, respectively. Figure 1(b) also contains the approximate bounds one would get when ignoring rare K decays. In this case, there are only two mass regions for each leptoquark: at low masses the bound depends on g/M and at high masses it depends on g^2/M . The approximate bounds can also be read from Tables I, II, and VII; they have the advantages of being true bounds, being relatively good approximations (the difference between the approximate and exact bounds on g is at most 15% for all masses) and most important, having simple functional dependence on the leptoquark pa-

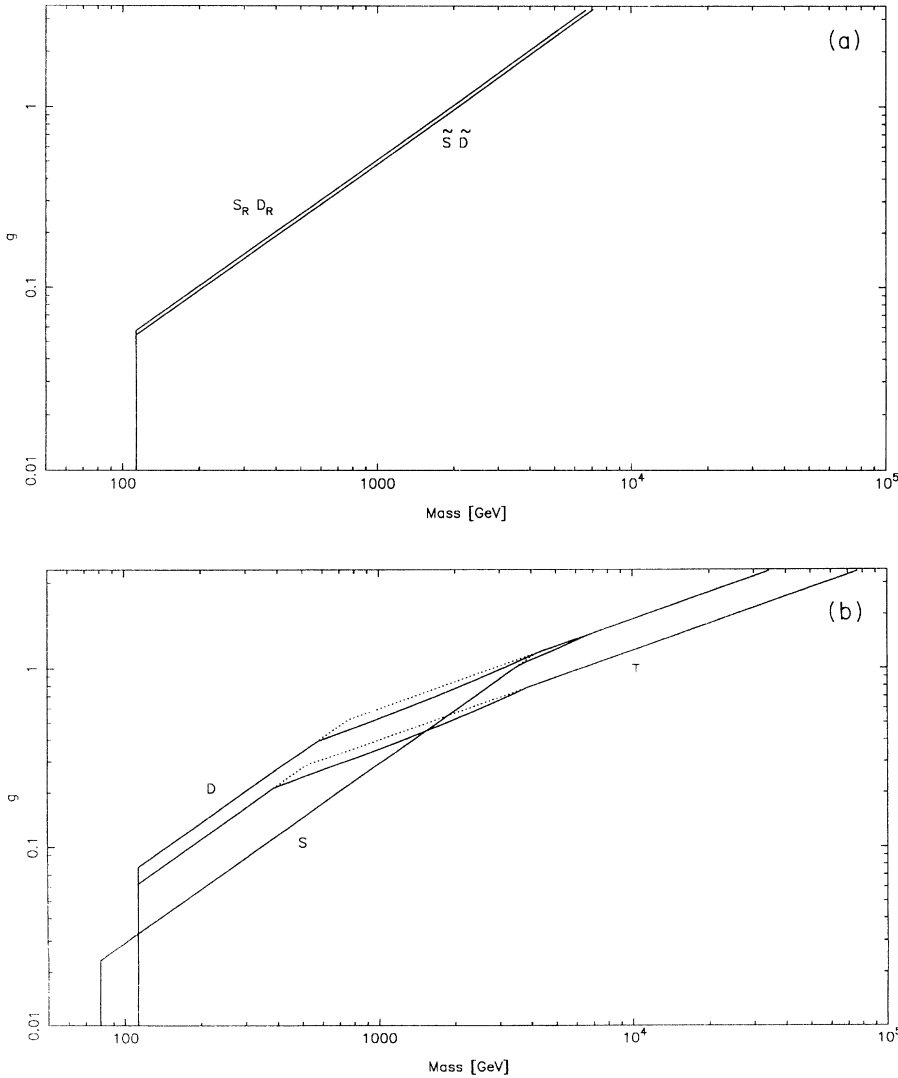


FIG. 1. (a) The overall bound on leptoquarks that couple to RH quarks. The regions above the lines are excluded. The graph is cut off at $g^2=4\pi$. (b) The overall bound on leptoquarks that couple to LH quarks. The regions above the lines are excluded. The graph is cut off at $g^2=4\pi$. The full lines show the exact bounds, the dotted lines the approximate bounds of Tables I, II, and VII.

TABLE VII. Combined $K^0\text{-}\bar{K}^0$ and $D^0\text{-}\bar{D}^0$ mixing lower bounds on M/g^2 at 95% C.L., in GeV. $M_{4\pi}$ and M_e are again the lower bounds on the mass when the coupling constant is set to $g^2=4\pi$ and e^2 , respectively. M_1 is the bound on the mass when the coupling constant is set to 1, and it is therefore also the bound on M/g^2 . Note the different functional dependence on the coupling constant relative to Tables I and II.

	S_L	D_L	T
$M_{4\pi}$	35 500	35 500	79 500
M_1	2 800	2 800	6 300
M_e	260	260	580

rameters. Figures 1(a) and 1(b) can be used to estimate the feasibility of various methods proposed for leptoquark searches [22]. Our bounds already exclude large regions in the parameter space that could be penetrated by some of these methods.

In Fig. 2 we restrict ourselves to the mass region which is subject to the direct searches at HERA. In this region our bounds on g are linear in M and can be read off Tables I and II. The figure compares our bounds to the first HERA results [1], and one sees that at the moment our bounds are far stronger than HERA's. In the future the situation will change, and HERA bounds *in this mass region* will become far stronger than ours.

Finally, in Table VIII we give the lower bound on the mass of the leptoquarks when the coupling constant is equal to the electromagnetic coupling e .

Note added. After this work was submitted for publication, we learned about another recently completed research on leptoquark bounds by S. Davidson, D. Bailey, and B. A. Campbell [Berkeley Report No. CfPA 93-th-29, hep-ph/9309310 (unpublished)].

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APPENDIX A: ADDITIONAL BOUNDS

In this appendix we present bounds from eD scattering, $p\bar{p} \rightarrow e^+e^-$ scattering, hadronic forward-backward asymmetry in e^+e^- machines, and universality in leptonic K decays. All these bounds are weaker than the ones in the body of the paper, but it is possible that in the future better experimental data and improved theoretical estimates will enable one to derive significant bounds from some of the processes discussed here. Also, we should note that the bounds we get from hadronic forward-backward asymmetry in e^+e^- scattering apply to lepto-

TABLE VIII. Final upper bounds on the leptoquark masses in GeV, at 95% C.L., when the coupling is equal to the electromagnetic coupling, $g=e$.

	S_L	S_R	\tilde{S}	D_L	D_R	\tilde{D}	T
$M \geq$	1040	600	630	440	600	630	750

quarks couplings to the electron and the *first or second* generation of quarks, and for \tilde{S} and \tilde{D} they apply to the couplings to the electron and any quark.

1. eD scattering

eD scattering provides information on the parity violating quantity $C_{2u} - C_{2d}/2$ (for the definition of the C_{2i} and their standard model values see Ref. [12]). The experimental result [23] and the standard model predictions are

$$\begin{aligned} (C_{2u} - C_{2d}/2)^{\text{expt}} &= -0.03 \pm 0.13, \\ (C_{2u} - C_{2d}/2)^{\text{SM}} &= -0.047 \pm 0.005. \end{aligned} \quad (\text{A1})$$

The additional contribution of a leptoquark is

$$\begin{aligned} \Delta(C_{2u} - C_{2d}/2)^{\text{LQ}} &= \left[\frac{g/M}{g_W/M_W} \right]^2 (-\eta_{S_L} + \eta_{S_R} - \eta_{\tilde{S}}/2 \\ &\quad + \eta_{D_L}/2 - \eta_{D_R} + \eta_{\tilde{D}}/2). \end{aligned} \quad (\text{A2})$$

The agreement between the experimental result and the standard model prediction leads to the bounds in Table IX. These are considerably weaker than the bounds derived from atomic parity violation and universality in leptonic π decays.

2. $p\bar{p}$ scattering to e^+e^-

$p\bar{p}$ scattering to e^+e^- was studied by the CDF group [24]. Analysis of the e^+e^- mass distribution led to bounds on the compositeness scales $\Lambda_{LL}^- \geq 2.2$ TeV and $\Lambda_{LL}^+ \geq 1.7$ TeV (for the definition of these scales see Ref. [25]). We did not make a detailed analysis, but estimate that similar bounds should apply to the leptoquarks, namely, we expect bounds of the order of $M/g \geq 2$ TeV/ $\sqrt{4\pi}$. These bounds are also weaker than the bounds in the body of the paper. Our conclusion is therefore that at present $p\bar{p} \rightarrow e^+e^-$ scattering does not provide useful bounds. We do, however, recommend that future analysis of this process be used for deriving bounds on leptoquarks since with improved statistics this may lead to interesting results.

TABLE IX. eD scattering 95% C.L. bounds on M/g , in GeV.

	S_L	S_R	\tilde{S}	D_L	D_R	\tilde{D}	T
$M_{4\pi}$	910	810	640	570	910	570	-
M_1	260	230	180	160	260	160	-
M_e	80	70	50	50	80	50	-

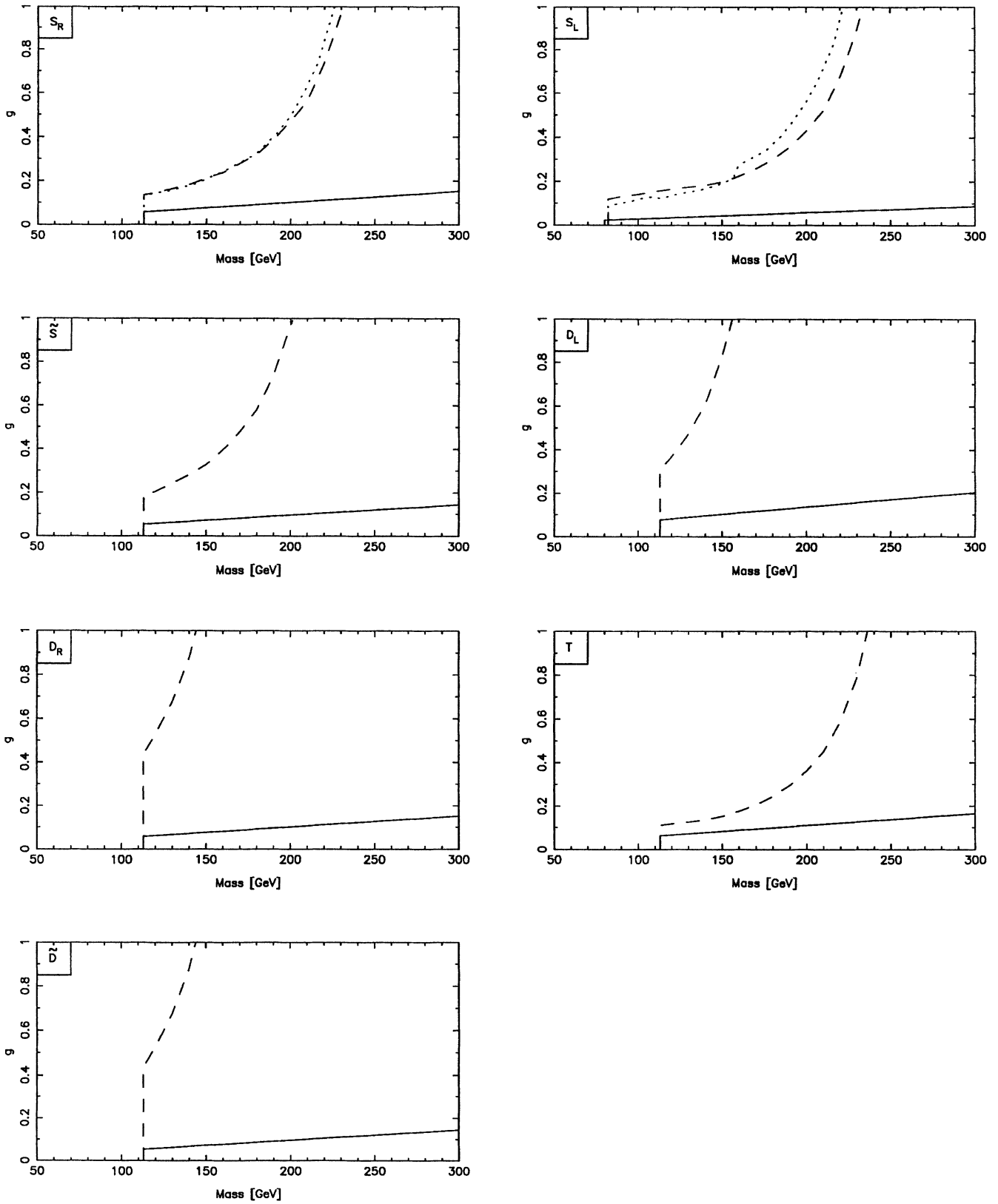


FIG. 2. Direct and indirect bounds on leptoquarks. The solid lines are our bounds, the dashed lines are the first bounds from the H1 group at HERA and the dotted lines the first bounds from the ZEUS group at HERA.

3. Hadronic forward-backward asymmetry in e^+e^- colliders

To avoid possible confusion, we first comment on an earlier work on a similar subject [26]. The authors of Ref. [26] studied the scattering processes $e^+e^- \rightarrow c\bar{c}$ and $e^+e^- \rightarrow b\bar{b}$ at $\sqrt{s} = 40$ GeV, and derived bounds on leptoquarks by requiring that the total cross section and the forward-backward asymmetry for both these processes deviate at most by a few percent from the standard model prediction. Although these are interesting bounds they are of *no relevance* to our study: The bounds of Ref. [26] apply to leptoquarks that couple to quarks of the second and third generation while we are interested in leptoquarks that couple to the first generation.

The relevant process for leptoquarks that couple to the first generation is $e^+e^- \rightarrow q\bar{q}$. Here a particular scattering is called “forward” if the negatively charged quark or antiquark scatters into the forward hemisphere of the electron beam. The hadronic forward-backward asymmetry of this process was studied at the SLAC e^+e^- storage ring PEP [27], at the DESY e^+e^- collider PETRA [28], at the KEK collider TRISTAN [29] and at LEP [30]. We chose to concentrate on the results of TRISTAN and LEP. Considering LEP, we have concentrated on OPAL measurements of the forward-backward asymmetry as these led to a somewhat more accurate determination of $\sin^2\theta_W$. We used the OPAL value $\sin^2\theta_W = 0.2321 \pm 0.0033$ to constrain leptoquarks in the following way: We calculated the forward-backward asymmetry in the standard model with the central OPAL value for $\sin^2\theta_W$. Then we defined “the 95% C.L. deviations” by repeating the calculation with $\sin^2\theta_W$ removed by $\pm 1.96\sigma$ from the central value. Finally, we calculated the asymmetry with $\sin^2\theta_W$ at its central value but with leptoquarks, and required that the deviation from the standard model prediction did not exceed “the 95% C.L. deviations.” This gives $M/g \geq 60$ – 80 GeV, the exact value depending on the leptoquark type. These bounds are far weaker than the bounds derived from atomic parity violation and universality in leptonic π decays.

Forward-backward asymmetry in TRISTAN leads to more interesting bounds on leptoquark parameters. Two groups, TOPAZ and AMY, have provided us with detailed data on their differential cross sections. Following the procedure used by TOPAZ to set bounds on the compositeness scale, we derived bounds on the leptoquarks parameters by comparing the experimentally measured differential cross section to the prediction of the leptoquark theory. Our results are summarized in Table X. Although these bounds are considerably weaker than the atomic parity violation and universality in leptonic π decay bounds we find them interesting since they apply to any leptoquark that couples chirally to the electron and

TABLE X. The 95% C.L. lower bounds on M/g , in GeV, as derived from TRISTAN data.

	S_L	S_R	\tilde{S}	D_L	D_R	\tilde{D}	T
$M_{4\pi}$	530	1600	880	1400	1300	480	680
M_1	150	440	250	390	370	140	190
M_e	45	130	75	120	110	40	60

TABLE XI. Universality in leptonic K decay 95% C.L. lower bounds on the coupling constant combination $g_1 g_2'$. The bounds are given as a function of the leptoquark mass M , with M in GeV.

	S_L	T
$ g_1 g_2' \leq$	$4.2 \times 10^{-6} \sin\theta_C M^2$	$4.2 \times 10^{-6} \sin\theta_C M^2$

to the first and/or the second quark generations. For the \tilde{S} and \tilde{D} leptoquarks these bounds apply also when they couple to the b quark of the third generation.

We should note that the bounds derived from TRISTAN apply to the quantity M/g only at the high mass region, where the leptoquark propagator can be approximated as $1/M^2$. At lower masses, propagator effects make it impossible to describe the exact bound in terms of a simple function of M and g . However, the bounds on M/g which are described in Table X still apply to a good approximation: There is only $\sim 3\%$ correction when $M = 200$ GeV, $\sim 10\%$ correction when $M = 113$ GeV, and $\sim 18\%$ correction when $M = 80$ GeV, relative to the bounds in the table. All the corrections *weaken* the bound. This weakening is because here the leptoquark runs in the t or u channel, with a propagator $1/(M^2 - t)$ or $1/(M^2 - u)$, which is suppressed relative to $1/M^2$.

4. Bounds from universality in leptonic K decays

Leptoquarks lead to deviations from universality in leptonic K decays. This leads to bounds on $g_1 g_2'$, which is equal, to a very good approximation, to $g_1' g_2'$. Universality in leptonic K decay therefore bounds the same coupling constant combination as do FCNC processes in the down sector.

Defining R_K to be the ratio of the decay rates of $K \rightarrow e\nu$ and $K \rightarrow \mu\nu$, we quote the observed ratio [12] and the standard model prediction (at tree level):

$$R_K^{\text{expt}} = (2.45 \pm 0.11) \times 10^{-5}, \quad (A3)$$

$$R_K^{\text{SM}} = \left(\frac{m_e}{m_\mu} \right)^2 \left(\frac{M_K - m_e}{M_K - m_\mu} \right)^2 = 2.57 \times 10^{-5}.$$

Leptoquarks modify the theoretical prediction for R_K to

$$R_K^{\text{LQ}} = R_K^{\text{SM}} \left[1 + 2 \frac{g_1 g_2'}{g_W^2 \sin\theta_C \cos\theta_C} \left(\frac{M_W}{M} \right)^2 (\eta_{S_L} - \eta_T) \right]. \quad (A4)$$

The agreement between the experimental result and the standard model value [Eqs. (A3)] lead to the bounds of Table XI. These bounds are considerably weaker than the rare K decay bounds of Sec. VI B.

APPENDIX B:

COMMENTS ON THE “WORKING ASSUMPTIONS”

In this appendix we will comment on our “working assumptions”; the assumption that there is at most one leptoquark multiplet and the assumption that there is no mass splitting within a multiplet.

At the mass region above ~ 1 TeV, we expect that our bounds still hold. Here electroweak breaking effects should be small: Mass splitting within a multiplet should be small relative to the average mass, since otherwise the ρ parameter gets unacceptably large contributions. Mixings among the multiplets can also be ignored when considering the processes discussed above. Then, since we do not expect exact or almost exact cancellations among the contributions of the various leptoquark multiplets, all our bounds should still hold.

At low masses one cannot ignore electroweak breaking. The parameter space then includes many mass parameters, as mass splitting within a multiplet as well as mixing become significant. It is hard to extract a clear picture in the general case, but it is possible to do so if we keep the assumption of a single leptoquark multiplet: First we note that the S_L , S_R , and \bar{S} leptoquarks contain one component each, and so the second assumption of no mass splitting is trivially true in their case. Therefore, all the bounds derived above still apply for these leptoquarks. With regard to the $SU(2)_W$ doublets and the triplet, the direct CDF bounds as well as the bounds from atomic

parity violation and universality in leptonic π decays still apply, with some modifications, to the components that couple to the electron. For D_R and \bar{D} , the direct CDF bound [$M \geq 113$ GeV] and the atomic parity violation bound (Table I) still apply to the $D^{(-5/3)}$ and $\bar{D}^{(-2/3)}$ component. For D_L , the CDF bound still applies to both components, and so does the atomic parity bound (see Table I) except the last is weakened by $\sim \sqrt{2}$. For the T multiplet, the cases of $T^{(1/3)}$ and $T^{(4/3)}$ are different: For $T^{(1/3)}$ the direct CDF bound is weakened and it now reads $M \geq 80$ GeV; the bound from universality in leptonic π decays still holds. For $T^{(4/3)}$ the direct CDF bound still applies without modification $M \geq 113$ GeV, but the bound from atomic parity violation is weakened by

$$\sqrt{2(Z+2N)/[2(Z+2N)+(2Z+N)]} \sim 0.83 .$$

The direct searches in CDF, atomic parity violation, and universality in leptonic π decays therefore still supply us with significant bounds on the leptoquark multiplet components that couple to the electron. These are also the components that can be searched for in HERA.

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