

## Bounds on vector leptoquarks

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We derive bounds on vector leptoquarks coupling to the first generation, using data from low energy experiments as well as from high energy accelerators. Similarly to the case of scalar leptoquarks, we find that the strongest indirect bounds arise from atomic parity violation and universality in leptonic  $\pi$  decays. These bounds are considerably stronger than the first direct bounds of the DESY  $ep$  collider HERA, restricting vector leptoquarks that couple with electromagnetic strength to right-handed quarks to lie above 430 GeV or 460 GeV, and leptoquarks that couple with electromagnetic strength to left-handed quarks to lie above 1.3 TeV, 1.2 TeV, and 1.5 TeV for the  $SU(2)_W$  singlet, doublet, and triplet, respectively.

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### I. INTRODUCTION

The ongoing leptoquark search at the DESY electron-proton machine HERA has stimulated renewed interest in these particles and their phenomenology. We have recently studied relevant data from low and high energy experiments in order to deduce bounds on the couplings of *scalar* leptoquarks [1]. Here we shall do the same for *vector* leptoquarks.

As in the case of the scalars, we are interested in the *unavoidable* bounds on the leptoquark couplings to the first generation. These are the relevant couplings for HERA as well as for many other leptoquark searches. We find that the strongest indirect bounds arise from low energy experiments: atomic parity violation, and universality in leptonic  $\pi$  decays. Our bounds are stronger than the first HERA results [2] and they also have important implications for various proposals for future indirect leptoquark searches at colliders [3], as they already exclude significant portions of the region in parameter space that such searches can penetrate.

The paper is organized as follows. In the next section the vector leptoquark multiplets and their couplings are presented. In Sec. III we review the bounds from direct leptoquark searches and in Sec. IV we derive the indirect bounds from atomic parity violation and universality in leptonic  $\pi$  decays. Section V reviews bounds that turn out to be less useful than those of Sec. IV. Section VI summarizes our results.

### II. THE VECTOR LEPTOQUARKS AND THEIR INTERACTIONS

The list of all possible vector leptoquark multiplets [4] includes the  $S$  and the  $\bar{S}$  leptoquarks in the  $(0)_{-2/3}$  and  $(0)_{-5/3}$  representations of  $SU(2)_W \times U(1)_Y$ , the  $D$  and  $\bar{D}$  leptoquarks in the  $(\frac{1}{2})_{5/6}$  and  $(\frac{1}{2})_{-1/6}$  representations, and the  $T$  leptoquark in the  $(1)_{-2/3}$  representation. Note that the scalar leptoquark multiplets [4] also include two  $SU(2)_W$  scalars, two doublets, and one triplet. The scalar and vector leptoquark multiplets differ however in two

important points. First, they carry different weak hypercharges. Second, they carry different fermion numbers:  $F = 3B + L$  (with  $B$  being the baryon number and  $L$  the lepton number) vanishes for the  $SU(2)_W$  doublet scalar leptoquarks but is  $(-2)$  for the  $SU(2)_W$  doublet vectors. The opposite happens for the  $SU(2)_W$  singlets and triplet: here  $F$  vanishes for the vectors and  $F = -2$  for the scalars.

As in the case of the scalar leptoquarks, we evade the strongest bounds on the vector leptoquarks by demanding that they have no diquark couplings, and that they couple chirally and diagonally to the first generation. We briefly repeat the discussion of the reasons for these demands.

(i) Diquark couplings are forbidden since these lead to nucleon decay [5] and therefore imply that the leptoquark mass is of the order of the grand unification theory (GUT) scale.

(ii) Chirality of the couplings means that the leptoquark couples either to left-handed (LH) quarks or to right-handed (RH) quarks, not to both. This requirement is due to the observation [6] that a nonchiral leptoquark that couples to the first generation gives a particularly enhanced contribution to  $\pi \rightarrow e\nu$ . To avoid a conflict with the observed universality in leptonic  $\pi$  decays, the nonchiral vector leptoquark must obey

$$M / \sqrt{|g_L g_R|} \geq 200 \text{ TeV} , \quad (2.1)$$

with  $M$  the leptoquark mass and  $g_L$  and  $g_R$  the couplings to the LH and RH quarks, respectively. This means that the leptoquark is very heavy or has very small couplings, and is consequently out of reach for present and near future colliders. The bound of Eq. (2.1) is two times stronger than the analogous bound for scalar leptoquarks [1]. We shall see that, in general, vector leptoquark contributions to various processes are enhanced relative to the scalar leptoquark contributions, although this will not necessarily imply that the bounds on the vector leptoquarks are stronger.

Some of the leptoquarks that are listed in the beginning

of this section are forced by their  $SU(2)_W \times U(1)_Y$  properties to be chiral. These are the  $\tilde{S}$  and the  $\tilde{D}$  that can couple only to RH quarks, and the  $T$  that can couple only to LH quarks. The other leptoquark multiplets, the  $S$  and the  $D$ , could couple both to LH and to RH quarks, but, since we require that couplings be chiral, we will from now on distinguish the  $S_L$  and  $D_L$  that couple to LH quarks from the  $S_R$  and  $D_R$  that couple to RH quarks.

(iii) Diagonality of the leptoquark couplings means that the leptoquark couples to a single generation of quarks and to a single generation of leptons. For HERA we are interested in the case where the leptoquarks couple only to the first generation. If this requirement is not fulfilled, the leptoquark induces flavor-changing neutral currents (FCNC) that lead to very strong bounds on its parameters [7,8]. In previous works [9,1] we have pointed out that strict diagonality is not really possible for leptoquarks that couple to LH quarks, since the couplings to the down quarks are Cabibbo-Kobayashi-Maskawa (CKM) rotated relative to the couplings to the up quarks. It is, however, possible to demand that such leptoquarks are approximately diagonal, that is, they couple mainly to the first generation, with their couplings to the second and third generations suppressed by  $O(\sin\theta_C)$  and  $O(|V_{13}| + |V_{12}||V_{23}|)$ , respectively,  $V$  being the CKM matrix.

The chirality and diagonality demands are very unlikely to be satisfied if the vector leptoquarks are gauge bosons: to see this, note that leptoquarks carry color. If they are gauge bosons, the gauge symmetry must be some extension of  $SU(3)_c$ , so that the leptoquarks together with the gluons are the gauge bosons of the extended group. If one now requires that the leptoquarks couple diagonally and chirally, these requirements must apply to the gluons as well; namely, the gluons couple to the first generation only, and furthermore, to quarks of a particular chirality only. This means that the theory should have at least two sets of gluons—those associated with the extended gauge group of the first generation quarks of the particular chirality, and those that are associated with all other quarks. There must then be some mechanism to break the two color groups to the diagonal one, leaving us with the usual single set of massless gluons. We now face several problems. First, each of the two color groups is anomalous due to the chirality requirement, and one needs to extend the theory further, adding fermions that will cancel the anomalies. Second, one must also extend the standard model Higgs sector in order to account for the masses of the first generation quarks and their mixing with quarks of other generations. At this stage the model-building task becomes too tedious and the result too cumbersome to be convincing. With these arguments in mind, we will in the following think of the vector leptoquarks as composites rather than fundamental particles.

In addition to our requirements on the leptoquark couplings, we also make some simplifying assumptions on the leptoquark spectrum: we assume that there is at most one leptoquark multiplet, and that the mass splitting within this multiplet is negligible. These assumptions simplify the presentation of the results since they leave us

with only two parameters: the leptoquark multiplet mass  $M$  and its coupling to the first generation,  $g$ .

There is a significant difference between the requirements on the leptoquark couplings and the assumptions on the leptoquark spectrum. If the requirements on the leptoquark couplings are satisfied, the most severe bounds on the leptoquark parameters are circumvented and we can concentrate on those bounds which are absolutely unavoidable; if these requirements are not satisfied, the bounds on the first generation couplings will just become stronger. In contrast, the assumptions that the leptoquark spectrum is a single multiplet, and that the mass splitting within the multiplet can be ignored, are made for convenience. If these assumptions do not hold, the bounds can change in either direction—they can become somewhat weaker or somewhat stronger, but, as discussed in [1], dramatic changes are unlikely.

We now introduce our notation. The couplings of the leptoquarks that couple to RH quarks are given by

$$\begin{aligned}\mathcal{L}_{S_R} &= g\bar{e}\gamma^\mu d_R S_\mu^{(-2/3)}, \\ \mathcal{L}_{\tilde{S}} &= g\bar{e}\gamma^\mu u_R \tilde{S}_\mu^{(-5/3)}, \\ \mathcal{L}_{D_R} &= g(\bar{\nu}^c\gamma^\mu d_R D_\mu^{(1/3)} + \bar{e}^c\gamma^\mu d_R D_\mu^{(4/3)}), \\ \mathcal{L}_{\tilde{D}} &= g(\bar{\nu}^c\gamma^\mu u_R \tilde{D}_\mu^{(-2/3)} + \bar{e}^c\gamma^\mu u_R \tilde{D}_\mu^{(1/3)}),\end{aligned}\quad (2.2)$$

where the superscripts on the leptoquark fields indicate their electromagnetic charge. In the case of the vector leptoquarks that couple to LH quarks, we have 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 the CKM rotation  $g'_i = g_j V_{ji}$ :

$$\begin{aligned}\mathcal{L}_{S_L} &= \sum_i (g_i \bar{\nu}\gamma^\mu u_L^i + g'_i \bar{e}\gamma^\mu d_L^i) S_\mu^{(-2/3)}, \\ \mathcal{L}_{D_L} &= \sum_i \{g_i \bar{e}^c\gamma^\mu u_L^i D_\mu^{(1/3)} + g'_i \bar{\nu}^c\gamma^\mu d_L^i D_\mu^{(4/3)}\}, \\ \mathcal{L}_T &= \sum_i \{ \sqrt{2} g_i \bar{e}\gamma^\mu u_L^i T_\mu^{(-5/3)} \\ &\quad + (g_i \bar{\nu}\gamma^\mu u_L^i - g'_i \bar{e}\gamma^\mu d_L^i) T_\mu^{(-2/3)} \\ &\quad + \sqrt{2} g'_i \bar{\nu}\gamma^\mu d_L^i T_\mu^{(1/3)} \}.\end{aligned}\quad (2.3)$$

For these leptoquarks we define

$$g = \left[ \sum_i |g_i|^2 \right]^{1/2} = \left[ \sum_i |g'_i|^2 \right]^{1/2}. \quad (2.4)$$

$g$  is the overall strength of the Yukawa couplings, and our results are given as bounds in the  $g$ - $M$  plane. Note that the first generation couplings are equal to  $g$  to a very good approximation (up to 2–3%), since we require that the second and third generation couplings are suppressed by  $O(\sin\theta_C)$  and  $O(|V_{13}| + |V_{12}||V_{23}|)$ . In the following, the differences between  $g$ ,  $g_1$ , and  $g'_1$  will be ignored.

We also introduce the parameters  $\eta_I$ , with  $I$  running over all leptoquark multiplets:  $I = S_L, S_R, \tilde{S}, D_L, D_R, \tilde{D}$ ,

$T$ .  $\eta_I$  gets the value 1 when we consider a theory with the leptoquark  $I$ , and otherwise it vanishes.

### III. DIRECT BOUNDS

In this section we summarize the leptoquark bounds from  $e^+e^-$  and hadronic colliders, where one searches for leptoquark pair production via an intermediate vector boson. Since the leptoquark production mechanism in these machines depends only on the gauge properties of the leptoquark, the bounds are independent of the overall strength of the Yukawa couplings [the CERN Large Electron-Positron Collider (LEP) bounds are completely independent of the Yukawa couplings while the hadronic colliders' bounds depend only on the *ratio* between the leptoquark coupling to a charged lepton and the leptoquark coupling to a neutrino]. This is in contrast to indirect bounds (to be discussed in the following sections) and to the bounds derived from the direct searches at HERA, which strongly depend on the Yukawa couplings.

The LEP experiments have searched for *scalar* leptoquark pair production in  $Z$  decays. No evidence for such a decay mode was found and consequently LEP set a lower bound on the scalar leptoquark mass,  $M \gtrsim M_Z/2$  [10]. Since the signature of a vector leptoquark pair is very similar to that of a pair of scalar leptoquarks, the LEP bound applies to vector leptoquarks as well.

The UA2 [11] and the CDF and DO [12] Collaborations searched for first generation scalar leptoquark pairs produced via an intermediate gluon. No events were seen, so UA2, CDF and DO derived bounds on the leptoquark masses. The bounds depend on  $b$ , the branching ratio of the leptoquark decay to  $e^\pm$  and a jet, since the hadronic colliders' experiments cannot identify events in which both leptoquarks decayed to a neutrino and a jet, and CDF also cannot identify an event in which one of the leptoquarks decayed to a neutrino and a jet. The CDF bounds on scalar leptoquarks have been recently translated to bounds on vector leptoquarks [13]. The bounds on the vectors depend not only on  $b$ , but also on the "anomalous chromomagnetic moment" of the leptoquarks, which affects significantly the leptoquark production cross section. Here we will use only the weakest bounds that apply in the case of vanishing anomalous chromomagnetic moment,  $M \gtrsim 150$  GeV for  $b = \frac{1}{2}$  and  $M \gtrsim 180$  GeV for  $b = 1$ . The  $S_L$  vector leptoquark has  $b = \frac{1}{2}$  and therefore only the weaker bound  $M \gtrsim 150$  GeV applies to it. All the other vector leptoquark multiplets contain at least one component with  $b = 1$ . Using our assumption of no mass splitting within a multiplet, we therefore find that all the vector leptoquarks but  $S_L$  are heavier than 180 GeV.

### IV. INDIRECT BOUNDS

In this section we will discuss the strongest indirect bounds that we find for vector leptoquarks. These arise from two low energy experiments, atomic parity violation and universality in leptonic  $\pi$  decays.

Atomic parity violation in cesium is experimentally measured and theoretically calculated to a high accuracy. It has been advocated for some time that this process

should give strong bounds on leptoquarks [14], and in [1] we found that this was indeed the case for scalar leptoquarks. We now repeat the analysis for the vectors. We look at the cesium "weak charge" defined by

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

with  $C_{1u}$  and  $C_{1d}$  defined, e.g., in [15] and with  $Z=55$  and  $N \simeq 78$  for cesium. The latest experimental result [16] and the standard model (SM) estimate [17] for  $Q_W$  are

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

In a theory with a vector leptoquark (LQ), there is an additional contribution to  $Q_W$ , given by

$$\begin{aligned} \Delta Q_W^{\text{LQ}} &= 4 \left[ \frac{g/M}{g_W/M_W} \right]^2 \\ &\times [(2Z+N)(\eta_{\tilde{S}} - \eta_{D_L} + \eta_{\tilde{D}} - 2\eta_T) \\ &\quad + (Z+2N)(-\eta_{S_L} + \eta_{S_R} - \eta_{D_L} + \eta_{D_R} - \eta_T)]. \end{aligned} \quad (4.3)$$

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 vector leptoquark contribution to  $Q_W$  can be derived from the scalar leptoquark contribution of [1] by (i) exchanging  $Z$  and  $N$ ; (ii) multiplying by a minus sign, and (iii) enhancing the contribution by a factor of 2. Despite this enhancement, atomic parity violation bounds on vector leptoquarks are not always stronger than the corresponding bounds on the scalar leptoquarks. This is due to the sign of the leptoquark contribution, which has a significant effect on the bound.

Universality in leptonic  $\pi$  decays had been used to derive a bound on the scalar leptoquark  $S_L$  already in 1986 [8]. In [1] we updated this bound and added the corresponding bound for the  $T$  scalar leptoquark. Here we repeat the analysis and find bounds on the  $S_L$  and  $T$  vector leptoquarks. The quantity that is measured and

TABLE I. Atomic parity violation 95% C.L. lower bounds on the ratio  $M/g$ , in GeV. The bounds are presented in three equivalent ways:  $M_{4\pi}$  is the lower bound on the leptoquark mass when the coupling becomes nonperturbative  $g^2 = 4\pi$ ,  $M_1$  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  $g=e$ .

|            | $S_L$  | $S_R$ | $\tilde{S}$ | $D_L$  | $D_R$ | $\tilde{D}$ | $T$    |
|------------|--------|-------|-------------|--------|-------|-------------|--------|
| $M_{4\pi}$ | 10 000 | 5300  | 5000        | 14 000 | 5300  | 5000        | 17 000 |
| $M_1$      | 2 900  | 1500  | 1400        | 4 100  | 1500  | 1400        | 4 900  |
| $M_e$      | 890    | 460   | 430         | 1 200  | 460   | 430         | 1 500  |

calculated is  $R = B(\pi \rightarrow e\nu) / B(\pi \rightarrow \mu\nu)$ . There are two recent measurements of  $R$ , one by TRIUMF [18], the other by PSI [19]. Combining their results we find

$$R^{\text{expt}} = (1.2310 \pm 0.0037) \times 10^{-4}. \quad (4.4)$$

The theoretical standard model (SM) calculation by Marciano and Sirlin has been updated [20] and the error is considerably reduced:

$$R^{\text{SM}} = (1.2352 \pm 0.0005) \times 10^{-4}. \quad (4.5)$$

The theoretical prediction in a theory with a vector leptoquark is

$$R^{\text{LQ}} = R^{\text{SM}} \left[ 1 + 2 \left( \frac{g/M}{g_W/M_W} \right)^2 (\eta_{S_L} - \eta_T) \right]^2. \quad (4.6)$$

Equations (4.4)–(4.6) lead to the bounds of Table II. Note that leptonic  $\pi$  decays provide the strongest bound on the  $S_L$  vector leptoquark, while atomic parity violation supplies the strongest bounds for all other vector leptoquarks, including the  $T$ . Note also that, again, the vector leptoquark contribution is enhanced by a factor of 2 relative to that of the scalar leptoquarks.

It is interesting to observe that the two bounds discussed in this section reflect the consequences of our assumptions—the chirality and diagonality of the leptoquark couplings. Chirality of the leptoquark couplings implies that processes mediated by these particles violate parity, while diagonality of the couplings implies that the leptoquarks distinguish the generations and may therefore induce deviations from universality.

## V. OTHER BOUNDS

In this section we will discuss various processes that give weaker bounds on vector leptoquarks than those of atomic parity violation and leptonic  $\pi$  decays.

### FCNC processes

In [9,1] we showed that FCNC processes can give a significant bound on scalar leptoquarks that couple to LH quarks. This was based on three main observations. The first observation is that FCNC processes are unavoidable for leptoquarks that couple to LH quarks. The second observation is that if one has FCNC bounds from both quark sectors it is possible to combine them to a bound on the overall coupling  $g$ . The last observation, which is troublesome in the case of the vector leptoquarks, is that there are indeed FCNC bounds from both sectors. It is well known that there are FCNC bounds in the down sector, which arise from rare  $K$  decays. The fact that there

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

|            | $S_L$  | $T$  |
|------------|--------|------|
| $M_{4\pi}$ | 15 500 | 9000 |
| $M_1$      | 4 400  | 2500 |
| $M_e$      | 1 300  | 760  |

is also a significant FCNC bound in the up sector was pointed out in [9], where the one-loop contributions of leptoquarks to  $D^0\text{-}\bar{D}^0$  and  $K^0\text{-}\bar{K}^0$  mixing were discussed. The problem with vector leptoquarks is that the one-loop calculation is not a clear procedure: we have pointed out that a vector leptoquark is unlikely to be fundamental. If it is composite, its loop contribution to neutral meson mixing diverges and it should be cut off at the compositeness scale. This cutoff procedure is not well defined since we do not know what is the appropriate compositeness scale to be used although we believe it is similar in size to the leptoquark mass; also, one should take into account other contributions that may arise from the underlying theory, but are unknown to us. We therefore do not attempt to extract bounds on vector leptoquarks from  $D^0\text{-}\bar{D}^0$  mixing, and have no bound on  $g$  from FCNC processes.

### Bounds from other processes

We have studied bounds that can arise from  $eD$  scattering, from the observed  $e^+e^-$  mass distribution in  $p\bar{p} \rightarrow e^+e^- + \text{any}$ , and from the hadronic forward-backward asymmetry in an  $e^+e^-$  machine. We find that the case of vector leptoquarks is similar to that of scalar leptoquarks, in that all these processes give weaker bounds than atomic parity violation and leptonic  $\pi$  decays. We now briefly review our results on these processes.

$eD$  scattering probes the parity-violating quantity  $C_{2u} - C_{2d}/2$ . The contribution of vector leptoquarks to this quantity is given by

$$\Delta(C_{2u} - C_{2d}/2)^{\text{LQ}} = \left( \frac{g/M}{g_W/M_W} \right)^2 \times (-\eta_{S_L} + \eta_{S_R} - 2\eta_{\bar{S}} - \eta_{D_L} - \eta_{D_R} + \eta_{\bar{D}} + 2\eta_T). \quad (5.1)$$

Comparing the experimental value ( $-0.03 \pm 0.13$ ) to the standard model value ( $-0.047 \pm 0.005$ ) [15] leads to the bounds of Table III, which are considerably weaker than those of the previous section.

Turning to  $p\bar{p}$  scattering to  $e^+e^-$ , we note that the CDF Collaboration [21] derived bounds of the order of 2 TeV on the compositeness scale by studying the mass distribution of the electron-positron system. In [1] we deduced that similar bounds should apply to scalar leptoquarks, namely,  $M_{4\pi} \gtrsim 2$  TeV. Here we extend this to vector leptoquarks. The bound for vector leptoquarks is stronger by a factor of  $\sqrt{2}$  since the coefficient of the

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

|            | $S_L$ | $S_R$ | $\bar{S}$ | $D_L$ | $D_R$ | $\bar{D}$ | $T$  |
|------------|-------|-------|-----------|-------|-------|-----------|------|
| $M_{4\pi}$ | 890   | 840   | 1270      | 890   | 890   | 840       | 1170 |
| $M_1$      | 250   | 240   | 360       | 250   | 250   | 240       | 330  |
| $M_e$      | 80    | 70    | 110       | 80    | 80    | 70        | 100  |

four-Fermi operator, e.g.,  $\bar{q}_L \gamma^\mu q_L \bar{e}_L \gamma^\mu e_L$ , is enhanced by a factor of 2 relative to the case of the scalars. The bound for vector leptoquarks therefore reads  $M_{4\pi} \gtrsim 3$  TeV. Note that for leptoquarks that couple to RH quarks this bound is weaker only by a factor of  $\sim 2$  than the atomic parity violation bound. It may therefore be worthwhile to repeat the CDF analysis with more data and apply it specifically to vector leptoquarks.

Considering hadronic forward-backward asymmetries in  $e^+e^-$  machines, the process we look at is  $e^+e^- \rightarrow q\bar{q}$ , where a particular scattering is called ‘‘forward’’ if the negatively charged quark or antiquark scatters into the forward hemisphere of the electron beam. Hadronic forward-backward asymmetry was studied at the SLAC  $e^+e^-$  storage ring PEP [22], the DESY  $e^+e^-$  collider PETRA [23], the KEK collider TRISTAN [24], and at LEP [25]. We concentrated on the results of TRISTAN and LEP, and found that TRISTAN data give the stricter bounds on the leptoquark parameters. Using the detailed data on differential cross sections provided to us by the

TABLE IV. The 95% G.L. lower bounds on  $M/g$ , in GeV, derived from TRISTAN data. For the  $\bar{D}$  leptoquark there is also a small allowed region at  $142 \text{ GeV} \lesssim M_1 \lesssim 149 \text{ GeV}$ .

|            | $S_L$ | $S_R$ | $\bar{S}$ | $D_L$ | $D_R$ | $\bar{D}$ | $T$  |
|------------|-------|-------|-----------|-------|-------|-----------|------|
| $M_{4\pi}$ | 1300  | 800   | 1550      | 2700  | 1400  | 1950      | 1200 |
| $M_1$      | 380   | 230   | 440       | 750   | 400   | 550       | 340  |
| $M_e$      | 110   | 70    | 130       | 230   | 120   | 170       | 100  |

TOPAZ and AMY Collaborations, we derived bounds on vector leptoquark parameters by comparing the experimentally measured differential cross section to the prediction of the leptoquark theory. Our results are summarized in Table IV. We should note that the bounds in this table apply to heavy leptoquarks (of  $\sim 1$  TeV and up). The bounds on the couplings of lighter leptoquarks are somewhat weaker (by up to 6%). These bounds are again considerably weaker than the atomic parity violation and

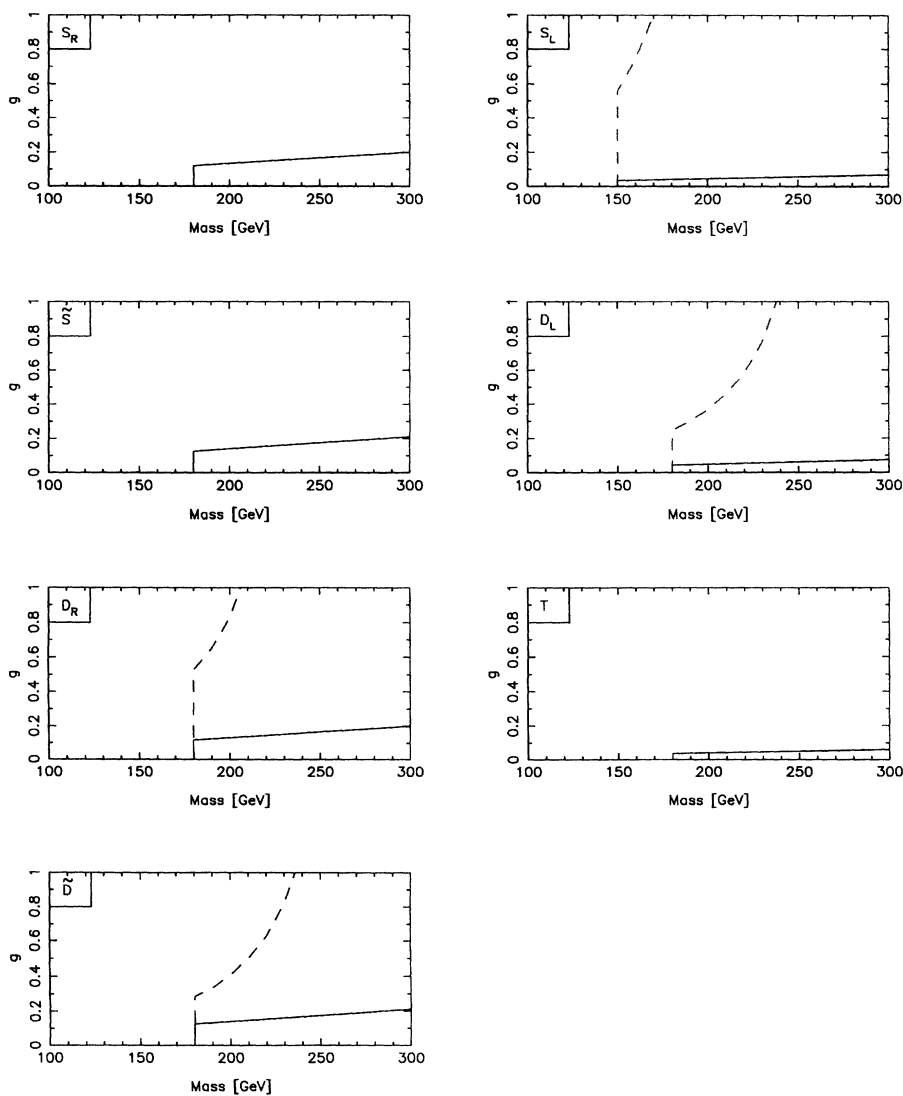


FIG. 1. Our indirect bounds (full line) compared with the direct bounds (dashed line) of the H1 group of HERA [2]. Note that for three of the leptoquark multiplets,  $S_R$ ,  $\bar{S}$ , and  $T$ , HERA does not yet provide any bounds in the mass region allowed by the CDF direct bound  $M \geq 180$  GeV.

the leptonic  $\pi$  decay bounds. We still find them interesting since they apply to any leptoquark that couples chirally to the electron and to the first and/or the second quark generations. For the  $S_R$  and the  $D_R$  leptoquarks, these bounds apply also when they couple to the  $b$  quark of the third generation.

## VI. SUMMARY

Our bounds on vector leptoquarks are summarized in Table V, which combines the results of Tables I and II. Note in particular the last row in this table: Vector leptoquarks that couple with electromagnetic strength are excluded far above HERA's kinematical limit of 300 GeV (the weakest bound, applying to  $\tilde{S}$  and  $\tilde{D}$ , reads  $M_e \geq 430$  GeV).

In Fig. 1 we compare our bounds with the first results from HERA in the mass range that is bounded from below by the CDF direct bound (150 GeV for  $S_L$  and 180 GeV for all other leptoquark multiplets) and from above by HERA's kinematical limit ( $M \lesssim 300$  GeV). Clearly, our bounds at the moment are far more strict. In the future HERA's results should improve considerably and will then win over our bounds in part of this mass range. As for higher leptoquark masses, there are some suggestions in the literature to search for them at HERA via indirect effects [3]. However, significant portions of the regions in parameter space that can be penetrated into via

TABLE V. Summary of the 95% G.L. lower bounds on the ratio  $M/g$ , in GeV, for vector leptoquarks.

|            | $S_L$  | $S_R$ | $\tilde{S}$ | $D_L$  | $D_R$ | $\tilde{D}$ | $T$    |
|------------|--------|-------|-------------|--------|-------|-------------|--------|
| $M_{4\pi}$ | 15 500 | 5300  | 5000        | 14 400 | 5300  | 5000        | 17 400 |
| $M_1$      | 4 400  | 1500  | 1400        | 4 100  | 1500  | 1400        | 4 900  |
| $M_e$      | 1 300  | 460   | 430         | 1 200  | 460   | 430         | 1 500  |

indirect methods at HERA (and at other colliders) are already excluded by our indirect low energy bounds of Table V.

Finally, we wish to stress again that the bounds in Table V are the weakest possible bounds on vector leptoquarks, and apply to leptoquarks that couple chirally and diagonally to the first generation. As we discussed in Sec. II, *fundamental* vector leptoquarks (gauge bosons) are not likely to obey the chirality and diagonality requirements. The bounds on their couplings are therefore so strong that such particles are beyond the discovery limit of present and near future colliders.

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