Much ado about leptoquarks: A comprehensive analysis

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We examine the phenomenological implications of a $\sim$200 GeV leptoquark in light of the recent excess of events at DESY HERA. Given the relative predictions of events rates in e^+p versus e^-p, we demonstrate that classes of leptoquarks may be excluded, including those contained in E_6 grand unified theory (GUT) models. It is shown that future studies with polarized beams at HERA could reveal the chirality of the leptoquark fermionic coupling and that given sufficient luminosity in each $e^{\pm}_{L,R}$ channel the leptoquark quantum numbers could be determined. The implications of 200–220 GeV leptoquarks at the Fermilab Tevatron are examined. While present Tevatron data most likely exclude vector leptoquarks and leptogluons in this mass region, it does allow for scalar leptoquarks. We find that while leptoquarks have little influence on Drell-Yan production, further studies at the Main Injector may be possible in the single production channel provided the Yukawa couplings are sufficiently large. We investigate precision electroweak measurements as well as the process $e^+e^- \to q\bar{q}$ at CERN LEP II and find they provide no further restrictions on these leptoquark models. We then ascertain that cross section and polarization asymmetry measurements at the Next Linear Collider (NLC) provide the only direct mechanism to determine the leptoquark's electroweak quantum numbers. The single production of leptoquarks in γe collisions by both the back-scattered laser and Weisacker-Williams techniques at the NLC is also discussed. Finally, we demonstrate that we can obtain successful coupling constant unification in models with leptoquarks, both with or without supersymmetry. The supersymmetric case requires the GUT group to be larger than SU(5) such as flipped $SU(5)\times U(1)_X$. [S0556-2821(97)04019-8]

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I. INTRODUCTION

The apparent symmetry between the quark and lepton generations is a mysterious occurrence within the standard model (SM) and has inspired many theories which go beyond the SM to relate them at a more fundamental level. As a result many of these models naturally contain leptoquarks, or particles that couple to a lepton-quark pair. Theories which fall in this category include, composite models with quark and lepton substructure [1], the strong coupling version of the SM [2], horizontal symmetry theories [3], extended technicolor [4], and grand unified theories (GUT's) based on the gauge groups SU(5) [5], SO(10) with Pati-Salam SU(4) color symmetry [6], SU(15) [7], and superstring-inspired E_6 models [8,9]. In all cases, the leptoquarks carry both baryon and lepton number and are color triplets under $SU(3)_C$. In models where baryon and lepton number are separately conserved, which includes most of the above cases, leptoquarks can be light (of order the electroweak scale) and still avoid conflicts with rapid proton decay. Their remaining properties, such as spin, weak isospin, electric charge, chirality of their fermionic couplings, and fermion number, depend on the structure of each specific model. If leptoquarks were to exist we would clearly need to determine these properties in order to ascertain their origin.

An excess of events at large values of Q^2 have recently been reported [10] by both the H1 and ZEUS Collaborations at the DESY ep collider HERA in their neutral current deep inelastic scattering (DIS) data. ZEUS has collected 20.1 pb^{-1} of integrated luminosity in e^+p collisions and observes five events with $Q^2 > 15\,000\ \mathrm{GeV}^2$ with $x > 0.45$ and $y > 0.25$, where x and y are the usual DIS scattering variables, while expecting two events from the SM in this region. H1 reports seven events in the kinematic region $m = \sqrt{xs} > 180$ GeV and $y > 0.4$, compared to a SM prediction of 1.83 ± 0.33 with $14.19 \pm 0.32\ pb^{-1}$ of integrated luminosity. Clearly, the statistical sample is too small at present to draw any conclusions and it is likely that this excess is merely the result of a statistical fluctuation. Another possibility is that this discrepancy is the result of deviations from current parton distribution parametrizations at large x. This case, however, has been examined by the H1 and ZEUS Collaborations [10] and is found to be unlikely. Also, such large modifications in the parton densities would most likely result in disagreement with the dijet data samples at the Tevatron [11,12]. It is also possible that this HERA data might signal the first hint of physics beyond the SM. Such an excess in event rate at large Q^2 is a classic signature for compositeness if the events show no specific kinematic structure. This scenario has recently been analyzed [13] in light of the HERA data, with the result that an $eeqq$ contact interaction with a right-left helicity structure (in order to avoid the constraints arising from atomic parity violation data discussed below) and a scale of $\sim$3 TeV is consistent with the data. However, if instead, the events cluster in x while being isotropic in y, they would signal the production of a new particle. While the reconstructed values of the mass ($m = \sqrt{xs}$) of such a hypothetical particle show some spread between the two experiments, they are consistent within the evaluated errors, yielding a central value in the approximate range 200–220 GeV.

If this excess of events turns out to be the resonant production of a new particle, we will need to examine the possible classes of new lepton-hadron interactions which could give rise to such a signature. At present, there are three leading scenarios of this type: (i) models with leptogluons, (ii)

explicit R-parity violating interactions in supersymmetric theories, and (iii) leptoquarks. We now briefly discuss the first two cases, with the remainder of the paper being devoted to the third.

Color octet partners of ordinary leptons are expected to exist in composite models with colored preons [14]. These particles, denoted as leptogluons, are fermions, carry lepton number and couple directly to a lepton-gluon pair with an undetermined strength. This effective interaction may be written as

$$\mathcal{L}_{\rm eff}=\frac{g_s}{\Lambda}\,[\lambda_L\overline{L}\sigma^{\mu\nu}\not{\ell}^a_{8,L}+\lambda_R\overline{\not{\ell}}^a_{8,R}\sigma^{\mu\nu}e_R]G^a_{\mu\nu}\not{\ell}+\text{H.c.}, \quad (1)$$

where $G^a_{\mu\nu}$ is the gluon field strength tensor, Λ is the compositeness scale, L represents the lepton doublet under $\mathrm{SU}(2)_L$, and $\lambda_{L,R}$ parametrizes the unknown coupling. We note that this effective Lagrangian is nonrenormalizable. If the chiral symmetry in these models is broken by QCD effects, the leptogluons are expected [14] to have masses of order $\alpha_s\Lambda$, and hence could be as light as a few hundred GeV for compositeness scales in the TeV range. Leptogluons in this mass range would clearly reveal themselves in high-Q^2 DIS at HERA. A $\sim$200 GeV leptogluon would also be copiously produced at hadron colliders. In fact, as we will see below, present Tevatron data most likely excludes leptogluons in this mass region.

The second scenario for resonant new particle production listed above is that of supersymmetric theories with explicit R-parity violating interactions. The most general gauge and supersymmetry invariant superpotential (with minimal field content) contains the terms

$$\lambda_{ijk}L_iL_j\overline{E_k}+\lambda'_{ijk}L_iQ_j\overline{D_k}+\lambda''_{ijk}\overline{U_iD_j}\overline{D_k}, \quad (2)$$

where the first two terms violate lepton number (L), the third violates baryon (B) number, the λ's are *a priori* unknown Yukawa coupling constants, and the i,j,k are generational indices where $\mathrm{SU}(2)_L$ invariance demands that $i\neq j$. In the minimal supersymmetric standard model (MSSM) a discrete symmetry matter parity (or R parity) is applied to prohibit all these dimension four B- and L-violating operators. However, it is sufficient to ensure only that the B- and L-violating terms do not exist simultaneously in order to preserve nucleon stability. In fact, a discrete anomaly-free Z_3 symmetry, denoted as baryon parity, naturally allows for the L-violating operators, while forbidding the $\Delta B\neq 0$ operators [15]. The phenomenology of these models is strikingly different than in the MSSM, as elementary couplings involving an odd number of supersymmetric particles now exist. This results in the possible single production of superpartners and an unstable lightest supersymmetric particle. At HERA, the second L violating term in Eq. (2) can mediate single squark production. This possibility was first considered in Ref. [16], and later examined in detail in Ref. [17]. The relevant terms in the interaction Lagrangian for this case are

$$\mathcal{L}=-\lambda'_{ijk}[\tilde{u}^j_L\overline{d^k_R}e^i_L+(\tilde{d}^k_R)^*(\overline{e^i_L})^c u^j_L]+\text{H.c.} \quad (3)$$

The requirement of $\mathrm{SU}(2)_L$ invariance combined with the fact that the positrons must be scattered off of valence quarks in order to account for the event excess at HERA, leaves us with only one possible scenario, the production of charm or top squarks via the first term above. This case has been recently examined [18] in light of the data and will not be considered further here. However, we note that such singly produced squarks must also decay via their R-parity conserving interactions (e.g., $\tilde{q}\to q+\chi^0$) at competitive rates, and hence events with these signatures must also be observed. We will comment on some of the difficulties associated with GUT theories with R-parity violation below.

We now examine the third candidate scenario above, the existence of 200–210 GeV leptoquarks, in detail.

II. WHAT IS A LEPTOQUARK?

The interactions of leptoquarks (LQ's) can be described by an effective low-energy Lagrangian. The most general renormalizable $\mathrm{SU}(3)_C\times\mathrm{SU}(2)_L\times\mathrm{U}(1)_Y$-invariant leptoquark-fermion interactions can be classified by their fermion number, $F=3B+L$, and take the form [19]

$$\mathcal{L}=\mathcal{L}_{F=-2}+\mathcal{L}_{F=0}, \quad (4)$$

with

$$\begin{aligned}\mathcal{L}_{F=-2}=&(g_{1L}\overline{q^c_L}i\tau_2\not{\ell}_L+g_{1R}\overline{u^c_R}e_R)S_1+\tilde{g}_{1R}\overline{d^c_R}e_R\tilde{S}_1\\&+g_{3L}\overline{q^c_L}i\tau_2\vec{\tau}\not{\ell}_L\vec{S}_3+(g_{2L}\overline{d^c_R}\gamma_\mu\not{\ell}_L\\&+g_{2R}\overline{q^c_L}\gamma^\mu e_R)V_{2\mu}+\tilde{g}_{2L}\overline{u^c_R}\gamma^\mu\not{\ell}_L\tilde{V}_{2\mu}+\text{H.c.},\\ \mathcal{L}_{F=0}=&(h_{2L}\overline{u_R}\not{\ell}_L+h_{2R}\overline{q_L}i\tau_2e_R)R_2+\tilde{h}_{2L}\overline{d_R}\not{\ell}_L\tilde{R}_2\\&+(h_{1L}\overline{q_L}\gamma^\mu\not{\ell}_L+h_{1R}\overline{d_R}\gamma^\mu e_R)U_{1\mu}+\tilde{h}_{1R}\overline{u_R}\gamma^\mu e_R\tilde{U}_{1\mu}\\&+h_{3L}\overline{q_L}\vec{\tau}\gamma^\mu\not{\ell}_L\vec{U}_{3\mu}+\text{H.c.}, \quad (5)\end{aligned}$$

assuming the fermionic content of the SM. If the SM fermion content is augmented it is possible that new LQ interactions may arise. Here, q_L and $\not{\ell}_L$ denote the $\mathrm{SU}(2)_L$ quark and lepton doublets, respectively, while u_R, d_R, and e_R are the corresponding singlets. The indices of the leptoquark fields indicate the dimension of their $\mathrm{SU}(2)_L$ representation. The subscripts of the coupling constants label the lepton's chirality. For simplicity, the color and generational indices have been suppressed. Since, in general, these couplings can be intergenerational, there is the possibility of large, tree-level flavor changing neutral currents and flavor universality violations. As discussed in the next section, this can be avoided by employing the constraint that a leptoquark couple only to a single generation. We see that the leptoquark fermionic couplings are baryon and lepton number conserving, hence avoiding the conventional problems associated with rapid proton decay. Note that the leptoquarks with fermion number (F) of -2 (S and V) couple to $\not{\ell}q$, while the $F=0$ leptoquarks (R and U) have $\not{\ell}\overline{q}$ couplings. Once this effective Lagrangian is specified, the gauge couplings of the leptoquarks are completely determined. Thus, only the strength of the leptoquark's fermionic Yukawa couplings remain unknown. For calculational purposes, these couplings are generally scaled to the electromagnetic coupling:

$$\lambda_{L,R}=e\tilde{\lambda}_{L,R}, \quad (6)$$

TABLE I. Quantum numbers and fermionic coupling of the leptoquark states [19]. No distinction is made between the representation and its conjugate.

	Leptoquark	SU(5) rep.	Q	Coupling	B_{ℓ}
Scalars					
$F=-2$	S_{1L}	**5**	1/3	$\lambda_L(e^+\overline{u}),\lambda_L(\overline{\nu d})$	1/2
	S_{1R}	**5**	1/3	$\lambda_R(e^+\overline{u})$	1
	$\widetilde{S}_{1R}$	**45**	4/3	$\lambda_R(e^+\overline{d})$	1
	S_{3L}	**45**	4/3	$-\sqrt{2}\lambda_L(e^+\overline{d})$	1
			1/3	$-\lambda_L(e^+\overline{u}),-\lambda_L(\overline{\nu d})$	1/2
			−2/3	$\sqrt{2}\lambda_L(\overline{\nu u})$	0
$F=0$	R_{2L}	**45**	5/3	$\lambda_L(e^+u)$	1
			2/3	$\lambda_L(\overline{\nu u})$	0
	R_{2R}	**45**	5/3	$\lambda_R(e^+u)$	1
			2/3	$-\lambda_R(e^+d)$	1
	$\widetilde{R}_{2L}$	**10/15**	2/3	$\lambda_L(e^+d)$	1
			−1/3	$\lambda_L(\overline{\nu d})$	0
Vectors					
$F=-2$	V_{2L}	**24**	4/3	$\lambda_L(e^+\overline{d})$	1
			1/3	$\lambda_L(\overline{\nu d})$	0
	V_{2R}	**24**	4/3	$\lambda_R(e^+\overline{d})$	1
			1/3	$\lambda_R(e^+\overline{u})$	1
	$\widetilde{V}_{2L}$	**10/15**	1/3	$\lambda_L(e^+\overline{u})$	1
			−2/3	$\lambda_L(\overline{\nu u})$	0
$F=0$	U_{1L}	**10**	2/3	$\lambda_L(e^+d),\lambda_L(\overline{\nu u})$	1/2
	U_{1R}	**10**	2/3	$\lambda_R(e^+d)$	1
	$\widetilde{U}_{1R}$	**75**	5/3	$\lambda_R(e^+u)$	1
	U_{3L}	**40**	5/3	$\sqrt{2}\lambda_L(e^+u)$	1
			2/3	$-\lambda_L(e^+d),\lambda_L(\overline{\nu u})$	1/2
			−1/3	$\sqrt{2}\lambda_L(\overline{\nu d})$	0

where $\lambda_{L,R}$ generically represent the $g_{iL,R}$ and $h_{iL,R}$. We note that in extended technicolor theories, the leptoquarks (denoted there as P_3) have couplings which are proportional to the masses of the quark-lepton pair. In this case the qeP_3 coupling is clearly too small to be of interest to us here.

The quantum numbers and structure of the quark-lepton couplings are summarized in Table I for each leptoquark species [19]. For the couplings we list the helicity, relative strength, and fermion pairs with which a particular leptoquark may couple, using the convention $\overline{LQ}_{F=-2}\to\ell q$ and $\overline{LQ}_{F=0}\to\ell\overline{q}$. The leptoquark's branching fraction into charged leptons B_{ℓ} is also given. The weak isospin structure is denoted by the brackets. Due to gauge invariance we would expect all the leptoquarks within a given $SU(2)_L$ representation to be degenerate apart from loop corrections. For future reference we have also listed the SU(5) representations of lowest dimension within which the leptoquark can be embedded. Note that we have assumed the conventional assignments of the SM fermions to be in the **5** and **10** representations. Generally, only a subset of these possible leptoquark states are contained within a particular model. For example, the scalar $S_{1L,R}$ is the leptoquark present in superstring-inspired E_6 theories. One exception is the GUT based on SU(15) [7], which contains all 14 possible leptoquark states.

Using Eq. (5), the total leptoquark tree-level decay widths are easily calculated to be

$$\Gamma=\frac{\alpha m_{LQ}}{4}\sum_i\tilde{\lambda}_i^2=0.386\,\frac{m}{200\ \text{GeV}}\sum_i\tilde{\lambda}_i^2\ \text{GeV}\quad\text{scalars},$$

$$\frac{\alpha m_{LQ}}{6}\sum_i\tilde{\lambda}_i^2=0.258\,\frac{m}{200\ \text{GeV}}\sum_i\tilde{\lambda}_i^2\ \text{GeV}\quad\text{vectors},\tag{7}$$

where we have scaled the widths to a 200 GeV leptoquark in our numerical evaluation, and the sum extends over all possible decay modes. These states are clearly very narrow and hence are long-lived, especially for the values of $\tilde{\lambda}$ that are consistent with the low-energy constraints discussed in the next section. As pointed out by Kunszt and Stirling as well as Plehn *et al.*, QCD corrections to these widths are very small [20,21].

III. LOW-ENERGY CONSTRAINTS

As mentioned above, low-energy data places strong restrictions on the leptoquark Yukawa couplings. In this section we summarize the most relevant of these constraints.

As is well known, for a leptoquark to be sufficiently light

for it to be of phenomenological interest at existing or planned colliders, it must have essentially chiral couplings to fermions. Here, we give two examples which demonstrate this conclusion. (i) Consider a first generation leptoquark coupling to ue_R^- with strength λ_R, and to $d\nu_L$ with strength λ_L. A Fiertz transformation then yields the interaction

$$\mathcal{L}=\frac{\lambda_L\lambda_R}{2m_{LQ}^2}\,\overline{u_R}d_L\overline{e_R}\nu_L\,, \tag{8}$$

which gives a large contribution to the decay $\pi^+\to e^+\overline{\nu_e}$. Comparison with current data results [19,22,23] in the bound $m_{LQ}>200|\lambda_L\lambda_R|^{1/2}$ TeV, implying that at least one if not both of these Yukawa couplings must be small, if leptoquarks are to be light. If one of these couplings is sufficiently large in order to induce leptoquark-fermion interactions at an interesting level, then the coupling with the other handedness must essentially vanish, i.e., the couplings are chiral. (ii) One can also examine the leptoquark's contribution to the $g-2$ of the muon arising from a one loop penguin diagram involving a light quark and a leptoquark. In this case if couplings of both helicities are present, current data places the constraint [22] $m_{LQ}>1000\lambda_L\lambda_R$ TeV, and again we see that these couplings must be essentially chiral.

Even if the leptoquark-fermion couplings are chiral, strong constraints on their magnitude still arise from their potential contributions to a wide class of flavor-changing neutral currents and related phenomena. An exhaustive study of this class of transitions has been performed by Davidson, Bailey, and Campbell [22], and hence we will not repeat this type of investigation here. The results of this study show that most of the stronger bounds can be satisfied if the requirement that a given leptoquark couple to only one generation is imposed. This results in the nomenclature of first, second, and third generation leptoquarks found in the literature. Note that this restriction is more severe than the simple requirement of family number conservation at a single vertex. This is easily illustrated by examining the process $K\to\mu e$, which would receive a large tree-level contribution if leptoquarks were allowed to simultaneously couple to both the first and second families.

After the constraints of chiral and single generation couplings are imposed, there are two important remaining low-energy constraints arising from atomic parity violation (APV) and the universality testing decay $\pi\to e\nu$. Comparable but somewhat weaker bounds also follow from quark-lepton universality. These additional restrictions have been examined by Leurer [23] and also by Davidson *et al.* [22] for both cases of scalar and vector leptoquarks. We summarize these results in Table II (assuming that the LQ is not responsible for the small difference between the SM expectations for the APV ''weak charge'' and what is obtained experimentally). These values have now been updated to include the recent results of Wood *et al.* on APV in cesium [24] which are in good agreement with SM predictions [25] yielding $\Delta Q_W=1.09\pm0.93$. Note that these bounds are far from trivial. For example, we see from this table that a spin-0, $\widetilde{R}_{2L}$ leptoquark with a mass of 200 GeV must have $\widetilde{\lambda}<0.22$. As we will see below this is not far from the value suggested by the excess of events at HERA.

TABLE II. Combined limits on the ratio $m/\widetilde{\lambda}$ in GeV, where m is the leptoquark mass, for the leptoquarks multiplets from data on atomic parity violation and the decay $\pi\to e\nu$.

Leptoquark	Limit	Leptoquark	Limit
S_{1L}	1040	U_{1L}	1300
S_{1R}	844	U_{1R}	645
$\widetilde{S}_{1R}$	893	$\widetilde{U}_{1R}$	597
S_{3L}	763	U_{3L}	1993
R_{2L}	844	V_{2L}	1605
R_{2R}	617	V_{2R}	645
$\widetilde{R}_{2L}$	893	$\widetilde{V}_{2L}$	597

Other types of experiments give slightly weaker bounds on the Yukawa couplings for fixed leptoquark mass. For example, it is well known that precision measurements in deep inelastic neutrino scattering are sensitive to new particle exchanges. Using the latest CCFR results [26] we obtain the constraint $\widetilde{\lambda}_{iL,R}\lesssim 0.4-0.6$ for 200 GeV leptoquarks. NuTeV [26] may be able to improve this reach by a factor of 2. Older results, such as that from the SLAC polarized electron-Deuteron scattering experiment [27], are only sensitive to $\widetilde{\lambda}_{iL,R}$ of order unity or greater.

IV. LEPTOQUARKS AT HERA

Clearly, ep collisions are especially well suited for leptoquark production and offer striking signals [19,28,29]. Direct production contributes to DIS in either the neutral or charged current channel, through an s-channel resonance $e^{\pm}(\overline{q})\to\mathrm{LQ}$ with the subsequent decay to either $e^{\pm}(\overline{q})$ or $\nu_e(\overline{q})$ with a fixed branching fraction, depending on the leptoquark species. The final state with ν_e manifests itself as missing energy. Clearly, this s-channel exchange would yield distinctive, and due to the size of the width, narrow peaks in the x distributions at $x=m^2/s$. These peaks, however, are smeared by the detector resolution as well as QCD and QED radiative effects [30,31]. Additional smaller contributions are generated from u-channel leptoquark exchange. The fermion number of the leptoquark dictates whether it will contribute via s- or u-channel exchange in e^- versus e^+ scattering off of valence (q) or sea $(\overline{q})$ partons. For example, the $F=-2$ leptoquarks (S and V) mediate DIS through the s channel (u channel) in $e^+\overline{q}(e^+q)$ collisions, while the $F=0$ states are exchanged in the u channel (s channel) in $e^+\overline{q}(e^+q)$ collisions. In principle, this can be used to separate the production of $F=-2$ from $F=0$ leptoquarks from cross section measurements alone.

We first examine the expected event yield in the $e^{\pm}j$ channel at HERA for the production of the various leptoquark species. We concentrate on the case of scalar leptoquarks, as $\sim$200 GeV vector leptoquarks are most likely excluded by Fermilab Tevatron data as shown in the next section. The cross section is dominated by the s-channel resonance, and the narrow width of these states as seen in Eq. (7) justifies the use of the narrow width approximation. The differential cross section for leptoquark production can then be written as

TABLE III. Number of events for scalar leptoquark production in e^+p and e^-p collisions, scaled to 20 and 1 pb^{-1} of integrated luminosity, respectively, assuming $m=200$ GeV, $\lambda=0.1e$, and taking $0.25\leqslant y\leqslant 1.0$. The numbers in brackets indicate the corresponding expected event yield in the charged current channel.

Leptoquark	$N_{e^+}(20\ \text{pb}^{-1})$	$N_{e^-}(1\ \text{pb}^{-1})$
S_{1L}	0.054 [0.054]	0.591 [0.591]
S_{1R}	0.108	1.18
$\widetilde{S}_{1R}$	0.229	0.288
S_{3L}	0.512 [0.054]	1.17 [0.591]
R_{2L}	23.7	0.005
R_{2R}	29.3	0.017
$\widetilde{R}_{2L}$	5.58	0.012

$$\frac{d\sigma(ep\to \mathrm{LQ}\to ej)}{dy} = \frac{\pi^2\alpha}{s}\widetilde{\lambda}^2(\overline{q})(m^2/s,Q^2)B_{\not\ell}\begin{Bmatrix}1, & \text{scalar}\\ 6(1-y)^2, & \text{vector}\end{Bmatrix}. \quad (9)$$

For the case of scalar leptoquarks, we see that the production is isotropic in y, whereas the electroweak DIS background has a $1/y^2$ behavior. In obtaining the total cross section for scalar leptoquarks, we use the y-averaged parton densities

$$\langle q(x,sxy)\rangle = \frac{\int q(x,sxy)dy}{\int dy}, \quad (10)$$

with the range $0.25\leqslant y\leqslant 1.0$, and employ the Martin-Roberts-Stirling set A′ (MRSA′) distributions [32]. The resulting expected excess of events from scalar leptoquark production are displayed in Table III for e^+p and e^-p collisions, scaled to 20 and 1 pb^{-1} of integrated luminosity, respectively. Here we assume $m=200$ GeV and for purposes of demonstration we take $\widetilde{\lambda}=0.1$. The numbers in brackets represent the corresponding event rate in the $\not{p}_T j$ channel. Note that only two leptoquark species can contribute to charged current DIS assuming only the SM fermion content as shown in Eq. (5). We stress that the relative magnitudes of these event rates are fixed by the contributing parton densities and the luminosity. As expected, the S_i leptoquarks have significantly larger cross sections in electron (rather than positron) collisions, since the valence quark distributions contribute in this case. Thus, in order to account for the HERA data, the $F=-2$ scalar leptoquarks would also yield an excess of events in the ~ 1 pb^{-1} of e^-p data. For example, if the leptoquark contained in E_6 theories S_{1L} were to account for the observed e^+j excess, then it would also yield roughly 60 excess events in 1 pb^{-1} of e^-p data. Thus, unless there are significant event excesses hiding in the H1 and ZEUS e^-p data (which is not yet completely analyzed), we may exclude $F=-2$ S-type leptoquarks as the source of the HERA events. In contrast, $F=0$ scalar leptoquark production is suppressed in electron collisions. We see that in the case of $\widetilde{R}_{2L}$, the predicted number of events in the e^+j channel with the assumed coupling strength of $\widetilde{\lambda}\simeq 0.1$ is consistent with the data, while for $R_{2L,R}$ the coupling would have to be somewhat smaller with $\lambda\sim 0.03-0.04$ neglecting the potentially large QCD corrections.

TABLE IV. Number of events per 100 pb^{-1} for each electron charge and state of polarization for a 200 GeV scalar leptoquark at HERA assuming $0.4<y<1$, $\widetilde{\lambda}=0.1$, and $M_{ej}=200\pm 20$ GeV. These results have been smeared with a detector resolution of 5% in M_{ej}.

Leptoquark	N_L^-	N_R^-	N_L^+	N_R^+
SM background	51.7	28.7	9.98	20.0
S_{1L}	121.	28.7	9.98	20.4
S_{1R}	51.7	167.	10.8	20.0
$\widetilde{S}_{1R}$	51.7	63.0	11.5	20.0
S_{3L}	190.	28.7	9.98	23.5
R_{2L}	52.4	28.7	9.98	158.
R_{2R}	51.7	29.4	148.	20.0
$\widetilde{R}_{2L}$	53.2	28.7	9.98	54.4

If the leptoquark signature is verified by future data taking at HERA, it will be mandatory to determine its couplings. Clearly, the best method of accomplishing this at HERA is to use both $e^\pm p$ collisions and to take advantage of possible beam polarization [19,29]. (It is expected that polarization levels of $P\approx 50\%$ may be achievable at HERA in the future.) Table IV displays the total number of expected events, scaled to 100 pb^{-1}, assuming 100% beam polarization for $e^\pm_{L,R}p$ collisions for a 200 GeV scalar leptoquark of each type, subject to the cuts $0.4\leqslant y\leqslant 1.0$ and $M_{ej}=200\pm 20$ GeV to remove the SM background. In these calculations the full deep inelastic scattering amplitudes, including the exchanges in all channels, have been used. The numerical results justify our earlier use of the narrow width approximation. The results have also been smeared by a 5% mass resolution. It is clear from the table that knowledge of the ratio of cross sections, which are essentially free of QCD corrections, in the four channels will allow the leptoquark quantum numbers to be determined if sufficient statistics are available. For fixed values of λ, it has been shown [20,21] that the QCD corrections to the production of leptoquarks off of the valence partons can be as large as $+25\%$, but are somewhat smaller for the case of production off of sea quarks.

V. SIGNATURES AT THE TEVATRON

Leptoquarks may reveal themselves in several reactions at hadron colliders. They may be observed directly via pair or single production mechanisms or they may indirectly influence the lepton pair invariant mass spectrum in Drell-Yan processes. We examine each of these in this section.

Since leptoquarks are color triplet particles, their pair production [33,34] proceeds through gluon fusion or quark annihilation and is essentially independent of the Yukawa coupling λ. There is a potential contribution of order λ^2 via the reaction $q\overline{q}\to \mathrm{LQ}\overline{\mathrm{LQ}}$ with t-channel lepton exchange, however, this contribution is negligible for the size of Yukawa couplings of relevance here, $\lambda\sim O(10^{-1}e)$. The pair production of scalar leptoquarks thus mimics that of squarks. The

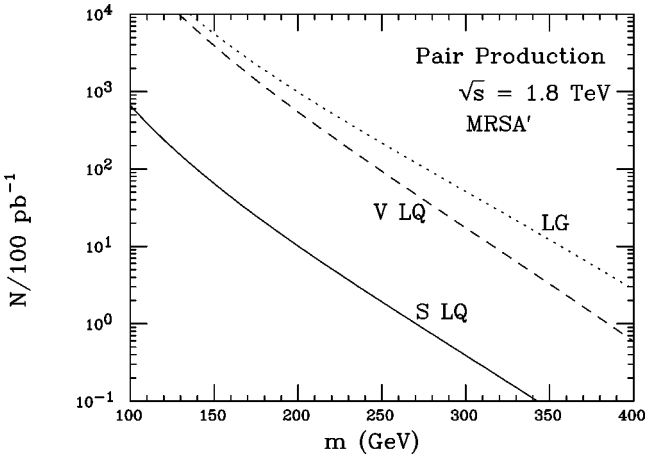

FIG. 1. Pair production cross sections at the Tevatron for scalar and vector leptoquarks, as well as leptogluons, corresponding to the solid, dashed, and dotted curves, respectively. Here, the gg and $q\bar{q}$ contributions are summed.

number of events expected at the Tevatron, scaled to 100 pb^{-1} of integrated luminosity, for the pair production of one generation of a single type of scalar leptoquark is displayed as the solid curve in Fig. 1. Here, we have employed the MRSA′ parton distributions [32], and omitted the K factor which has been calculated [35] for leptoquark production to be $K_{gg}=1+2\alpha_s\pi/3$ and $K_{qq}=1-\alpha_s\pi/6$ for the gluon fusion and quark annihilation subprocesses, respectively. For a 200 GeV scalar leptoquark, this yields an enhancement in the cross section by a factor of 1.16 giving $\sigma=0.117$ pb assuming $\mu^2=\hat{s}$. If instead $\mu^2=m^2$ is chosen, a larger cross section will result since we always have $\hat{s}>4m^2$. We note that the cross section falls rapidly, dropping by a factor of 1.32 between $m=200$ and 210 GeV with $\sigma(m=210\ \mathrm{GeV})=0.089$ pb. Somewhat larger cross sections are obtainable if the CTEQ [36] distribution functions are employed. We further note that a complete next leading order (NLO) calculation of scalar LQ pair production has now been completed by Krämer *et al.* which essentially reproduces the results obtained using the K-factor approach and a scale in the range $\mu^2=(0.25-4)m^2$ [37].

The signatures for leptoquark pair production are two jets accompanied by either $\ell^+\ell^-$, $\ell^\pm\not{p}_T$, or $\not{p}_T$, with a pair of jet$+\ell^{\pm,0}$ invariant masses being equal to the mass of the leptoquark. D0 has searched for the dijet with two or single charged lepton topologies in the electron and muon channels, and the Collider Detector at Fermilab (CDF) has searched in the dilepton+dijet case for all three lepton generations. For each generational coupling the most stringent bounds [38] are $m_{(e)}>175(147)$ GeV from D0, $m_{(\mu)}>180(140)$ GeV and $m_{(\tau)}>99$ GeV from CDF, with $B_{\ell}=1(0.5)$. D0 sets a 95% C.L. limit on the pair production cross section of scalar leptoquarks decaying into e^+e^-jj of $\sigma\lesssim 0.2$ pb^{-1}. This D0 bound is based on the observation of three events with a Monte Carlo background estimate of 2.85 ± 1.08 events arising from Drell-Yan, $t\bar{t}\to\ell\ell$, $Z\to\tau\tau\to\ell\ell$, $WW\to\ell\ell$ and fakes from QCD. Clearly the leptoquark $SU(2)_L$ representations which contribute to the cross section significantly more than that of a single leptoquark, e.g., R_{2R}, will have a more difficult time satisfying these bounds. We stress again that these constraints are independent of the value of λ.

CDF has yet to present results from a search for first generation leptoquarks from runs 1A and 1B, which contain a combined data sample of approximately 110 pb^{-1}. Based on our cross section above, we would expect CDF to observe at most one signal event (taking $B_{\ell}=1$) depending exactly on the leptoquark mass (e.g., 200 versus 210 GeV) and the details of their selection criterion, plus an unknown amount of background. Until all of these numbers become available we cannot attempt to combine the CDF and D0 results to obtain a stronger mass bound without speculating upon the details of the CDF data and a thorough understanding of the common systematics of the two experiments. However, we would not expect a combined D0/CDF bound to significantly exceed 220 GeV for $B_{\ell}=1$.

In order to compute the pair production cross section for vector leptoquarks (V) we need to determine both the trilinear gVV and quartic $ggVV$ couplings. In any realistic model that contains fundamental vector leptoquarks, they will be the gauge bosons of some extended gauge group. Hence gauge invariance will completely specify the gVV and $ggVV$ couplings in such a manner as to guarantee that the subprocess cross section obeys tree-level unitarity, as is the hallmark of all gauge theories. However, vector leptoquarks could be a low-energy manifestation of a more fundamental theory at a higher scale, and they could be composite. In this unlikely case various anomalous gVV and $ggVV$ couplings could be present, one of which can be described by a chromomagnetic moment κ. A second anomalous term corresponding to a dimension-6 operator may also be present, with a proportionality constant λ_G as has been discussed by Blümlein *et al.* [34]. The κ term, however, represents the only dimension 4 anomalous coupling which conserves CP. In gauge theories κ takes on the value of unity while $\lambda_G=0$. The cross sections for vector leptoquarks with $\kappa=1$ have been computed in Refs. [34,39,40]. In this case the total event rate, scaled again to 100 pb^{-1} of integrated luminosity, for VV production at the Tevatron is given by the dashed curve in Fig. 1 using the results of Hewett *et al.* Vector leptoquarks have the same signatures as discussed above for the scalar case, but with slight detailed variations in the production angular distribution due to the fact they are spin-1 particles. A reasonable estimate of the search reach can be obtained by employing the D0 bound on the cross section for e^+e^-jj events from scalar leptoquark production. We estimate that this procedure yields the constraint on first generation vector leptoquarks with $\kappa=1$ of $m\gtrsim 290$ GeV, placing this case out of the kinematic reach of HERA [41]. Clearly, the experiments themselves need to perform a detailed analysis in order to confirm this estimate.

The results in the more general case [34,39] of $\kappa\neq 0$ are displayed in Fig. 2 from Hewett *et al.* For the most general case where $\lambda_G\neq 0$, see Blümlein *et al.* in [34]. Here, the separate $q\bar{q}$,gg, and the total cross sections for vector leptoquark pair production with $m=200$ GeV are shown as a function of κ. We see that the cross section varies significantly with κ yielding larger or smaller values than the results given above for $\kappa=1$. In the worst case, the total cross section reaches its lowest value of $\sigma_{\mathrm{low}}\approx 0.6$ pb around $\kappa\approx -0.45$. This value of κ is, of course, much larger than one would expect in any realistic model but is considered here for generality. However, this value of σ_{low} is significantly

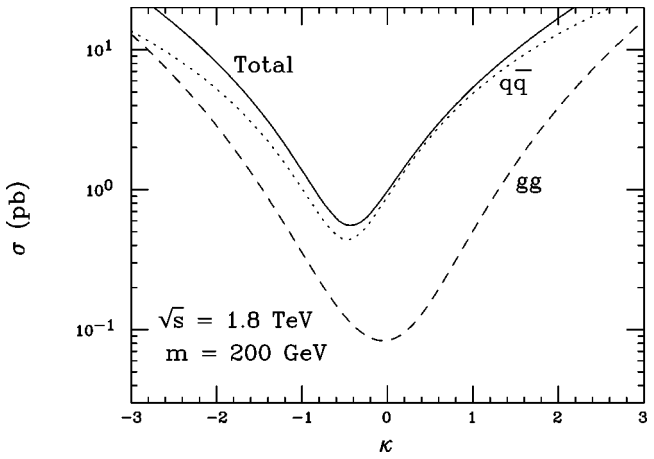

FIG. 2. κ dependence of the $q\bar{q}, gg$, and total vector leptoquark pair production cross sections at the Tevatron, represented by the dotted, dashed, and solid curves, respectively. The leptoquark mass is taken to be 200 GeV.

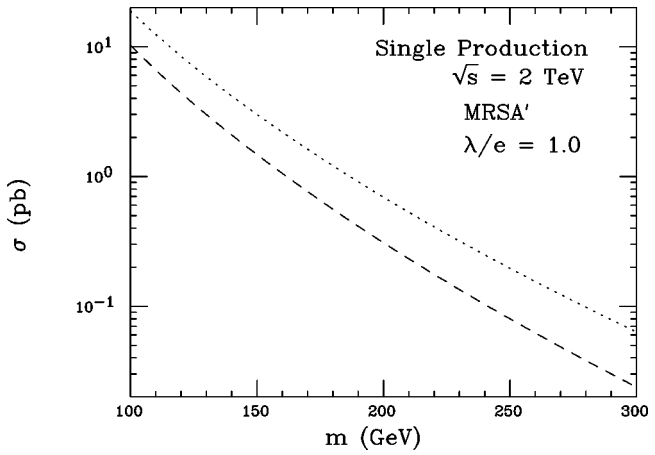

FIG. 3. Single production cross sections at the Tevatron for scalar leptoquarks as a function of mass from $gu(\bar{u})$ and $gd(\bar{d})$ fusion, corresponding to the dotted and dashed curves, respectively. Here, $\lambda/e=1$, and the K factor has been omitted.

larger than the D0 bound [38] of 0.2 pb and would again exclude 200 GeV vector leptoquarks for this κ with $B_l=1$. For all other values of κ, the cross section is comfortably large enough to be prohibited by D0. We remind the reader that we have neglected the K factors in this analysis; their inclusion will only strengthen our conclusions. If one allows λ_G also to be nonzero (see Blümlein *et al.* in Ref. [34]) then a fine tuning of both parameters allows for a reasonably small cross section. However, it is quite unlikely that these particular parameter values would be realized in a natural way.

Here, we also consider the case of pair production of leptogluons at the Tevatron. This process was considered in Refs. [42,43] and is also mediated by gg fusion and $q\bar{q}$ annihilation, similar to the production of any heavy colored fermion. However, since leptogluons are color octets, there is an enhanced color structure in this case compared to, e.g., top-quark pair production. The event rate, scaled to 100 pb^{-1}, is given by the dotted curve in Fig. 1. We see that this cross section is larger than that for both scalar and vector leptoquarks, and is roughly six times the top pair cross section. The D0 cross section bounds on e^+e^-jj events would clearly exclude 200 GeV leptogluons and could naively place the constraint $m_{LG}\gtrsim 325$ GeV.

Leptoquarks can also be produced singly at hadron colliders. The parton level subprocess responsible for single production is $qg\to \mathrm{LQ}+\ell$, where ℓ is a charged lepton or neutrino depending on the type of leptoquark. The diagrams for this process contain the QCD strong coupling at one vertex and the leptoquark Yukawa coupling at the other. The subprocess differential cross section for scalar leptoquarks is given by [33,44]

$$\frac{d\hat{\sigma}}{d\hat{t}}=\frac{\pi\alpha_s\alpha\tilde{\lambda}^2}{3\hat{s}^2}\left[\frac{\hat{s}+\hat{t}-m^2}{\hat{s}}+\frac{\hat{t}(\hat{t}+m^2)}{(\hat{t}-m^2)^2}+\frac{\hat{t}(2m^2-\hat{s})}{\hat{s}(\hat{t}-m^2)}\right], \tag{11}$$

where $\hat{t}=1/2(m^2-\hat{s})(1-\cos\theta)$ with θ being the quark-lepton scattering angle. For completeness we give the corresponding single production cross section for vector leptoquarks in the Appendix. Compared to pair production, this mechanism has the advantage of a larger amount of available phase space, but has the disadvantage in that it is directly proportional to the small Yukawa coupling. The total cross section at the Tevatron Main Injector and/or TeV33 (now taking $\sqrt{s}=2$ TeV) in the case of scalar leptoquarks with $\lambda/e=1$ for both $gu+g\bar{u}$ and $gd+g\bar{d}$ fusion is presented in Fig. 3. Note that for a $p\bar{p}$ collider, the gq and $g\bar{q}$ cross sections are equal. Here, we have again omitted the K factor (given by $K=1+3\alpha_s\pi/4$ for single production [35]), which enhances the cross section by a factor of $\simeq 1.25$. For a 200 GeV scalar leptoquark with coupling strength of $\lambda/e=0.1$ and including the K factor, our results show that we obtain approximately $\sim$39,87 events from $gd+g\bar{d}, gu+g\bar{u}$ fusion, respectively, with 10 fb^{-1} of integrated luminosity at the Main Injector/TeV33. This event rate should be sufficient to provide a very rough determination of the value of the Yukawa coupling λ. The signatures for this production mode are jet $+\ell^+\ell^-, +\ell^{\pm}\not{p}_T, +\not{p}_T$ and at least in the first case, should be easily detectable.

Indirect signals for leptoquarks may be observed in Drell-Yan production [45]. In addition to the usual s-channel γ and Z exchange in the SM, leptoquarks may also contribute to $q\bar{q}\to e^+e^-$ in t- or u-channel exchange, with the specific channel depending on the leptoquark type, via the Yukawa coupling. This new exchange will modify not only the invariant mass distribution, but also the angular distribution of the lepton pair. The parton level differential cross section for this process can be written as

$$\frac{d\sigma}{dMdydz}=\frac{K\pi\alpha^2}{6M^3}\sum_q\,[F_q^+G_q^++F_q^-G_q^-], \tag{12}$$

where M represents the invariant mass of the lepton pair, $z=\cos\theta^*$ with θ^* being the $\ell^+\ell^-$ center-of-mass scattering angle, K is the usual QCD correction factor with α_s evaluated at the scale M, and the sum extends over the appropriate partons. In the SM all quark flavors, in principle, contribute to this process, whereas, in the case of leptoquark exchange, only one or two quark flavors contribute. The parton density factors are given by

$$G_q^{\pm} = x_a x_b [q(x_a)\overline{q}(x_b) \pm q(x_b)\overline{q}(x_a)], \tag{13}$$

with $x_{a,b} = (M/\sqrt{s})e^{\pm y}$ as usual, and $F_q^{\pm}$ represent the even and odd kinematic functions, which are given in the Appendix for both the SM and leptoquark contributions.

The invariant mass distribution is obtained by integrating the differential cross section over the regions $-Y \leq y \leq Y$ and $-Z \leq z \leq Z$, where

$$Y = \min[y_{\max}, -\ln(M/\sqrt{s})],$$

$$Z = \min[\tanh(Y - |y|), 1], \tag{14}$$

where $y_{\max}$ represents the rapidity coverage of the detector or of the applied cuts. To calculate the forward-backward asymmetry, Eq. (12) is first integrated over the forward ($z>0$) and backward ($z<0$) regions separately (subject to $|z| \leq |Z|$) and then over y; the difference of the forward and backward cross sections divided by their sum then gives $A_{\rm FB}$. Explicitly, we define

$$\frac{d\sigma^+}{dM} = \left[\int_{y>0} dy + \int_{y<0} dy\right]\left[\int_{z>0} + \int_{z<0}\right]\left[\frac{d\sigma}{dM dy dz}\right] dz,$$

$$\frac{d\sigma^-}{dM} = \left[\int_{y>0} dy \pm \int_{y<0} dy\right]\left[\int_{z>0} - \int_{z<0}\right]\left[\frac{d\sigma}{dM dy dz}\right] dz, \tag{15}$$

where the $+$, $(-)$ sign is relevant for $\overline{pp}$, (pp) collisions. The forward-backward asymmetry is then given by

$$A_{\rm FB}(M) = \frac{d\sigma^-/dM}{d\sigma^+/dM}. \tag{16}$$

Figure 4 displays our results for (a) the Drell-Yan invariant mass spectrum and (b) forward-backward asymmetry in the electron channel with and without scalar leptoquark exchange at the Tevatron. Here, we have employed the present rapidity coverage of the CDF detector as used in their Drell-Yan analysis [46] $|y_{\max}| \leq 1$. We have assumed a scalar leptoquark mass of 200 GeV and Yukawa coupling strength of $\lambda/e = 1$. In this figure, the SM is represented by the solid curve, and the cases with left, right-handed leptoquark couplings to u (d) quarks correspond to the dashed (dot-dashed), dotted (dot-dashed) curves. We see that the influence of leptoquark exchange on this process is minimal, even for these large values of the couplings. It is clear that at the present level of statistics, the Tevatron experiments are not sensitive to leptoquark exchange in Drell-Yan production.

We next examine the level of sensitivity that will be achievable at the Main Injector with 2 fb^{-1} and $\sqrt{s} = 2$ TeV. Following Ref. [47], we enlarge the rapidity coverage to $|Y| < 2.5$ and construct 21 invariant mass bins, corresponding to four bins in steps of 10 GeV in the range $40 \leq M \leq 80$ GeV, five bins in steps of 4 GeV in the range $80 \leq M \leq 100$ GeV, five bins in steps of 20 GeV in the range $100 \leq M \leq 200$ GeV, five bins in steps of 40 GeV in the range $200 \leq M \leq 400$ GeV, and two bins in steps of 100 GeV in the range $400 \leq M \leq 600$ GeV. The bin integrated cross section and asymmetry are then obtained for both the SM and for the case with 200 GeV scalar leptoquark exchange. We determine the statistical error on these quantities in each bin, which are taken to be $\delta N = \sqrt{N}$ and $\delta A = \sqrt{(1-A^2)/N}$. The bin integrated results for the SM, along with the error associated with each bin, are displayed in Fig. 5. To evaluate what constraints may be placed on the leptoquark coupling we then perform a χ^2 analysis according to the usual prescription:

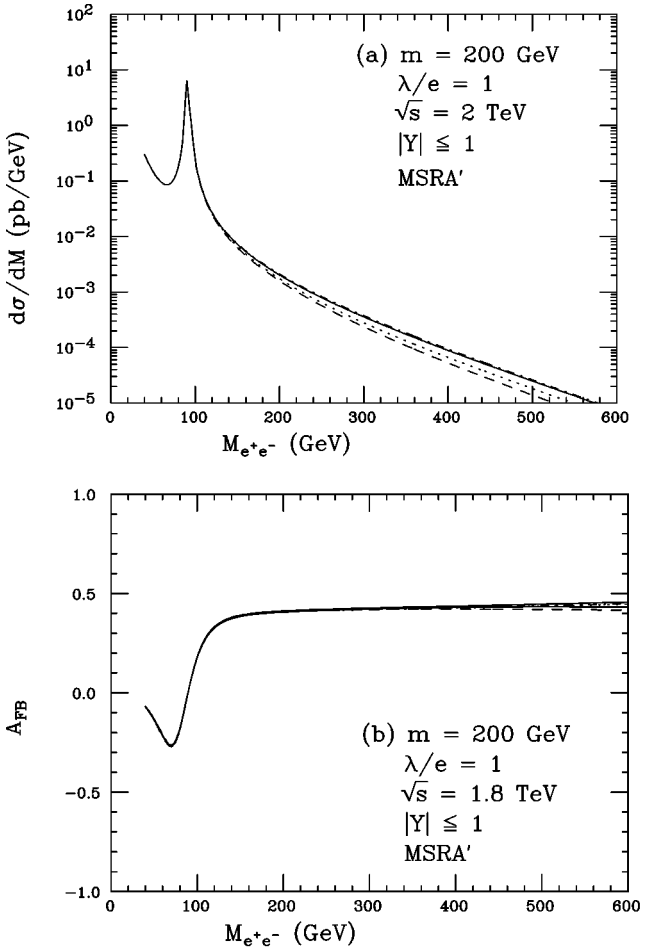

FIG. 4. (a) The lepton pair invariant mass distribution and (b) forward-backward asymmetry in Drell-Yan production for the SM (solid curve) and with 200 GeV scalar leptoquark exchange, assuming $\tilde{\lambda} = 1$, with left(right)-handed couplings to u quarks, corresponding to the dashed (dotted) curve, and left(right)-handed couplings to d quarks (dash-dotted curve for both cases).

$$\chi^2_i = \sum_{\rm bins} \left(\frac{Q_i - Q_i^{\rm SM}}{\delta Q_i}\right)^2, \tag{17}$$

where Q_i represents each observable quantity. The resulting χ^2 distribution, summing over both observables, is presented in Fig. 6 as a function of λ/e for the various scenarios of left(right)-handed leptoquark couplings to u and d quarks. We see that the 95% C.L. bounds (corresponding to $\Delta\chi^2 = 3.842$) on $\tilde{\lambda}$, are quite weak and are inferior to the present restrictions from low-energy data.

We briefly summarize this section by pointing out (i) present Tevatron data analyses easily allow for scalar leptoquarks in the 200–210 mass range, but exclude vector leptoquarks and leptogluons. (ii) If 200 GeV leptoquarks exist

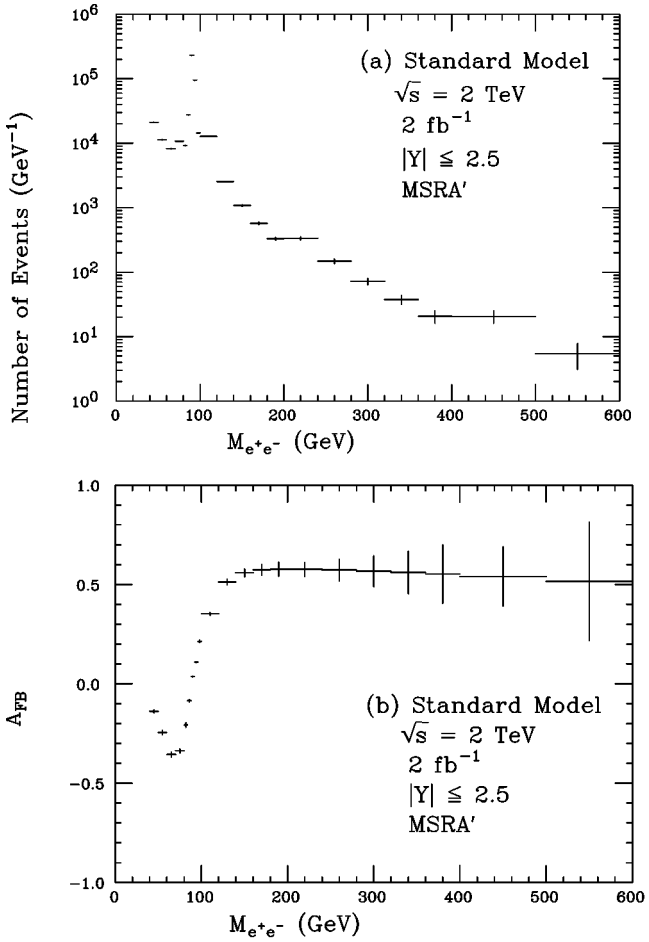

FIG. 5. Bin integrated lepton pair (a) invariant mass distribution and (b) forward-backward asymmetry for Drell-Yan production in the SM at the Main Injector. The vertical lines correspond to the expected statistical error in each bin.

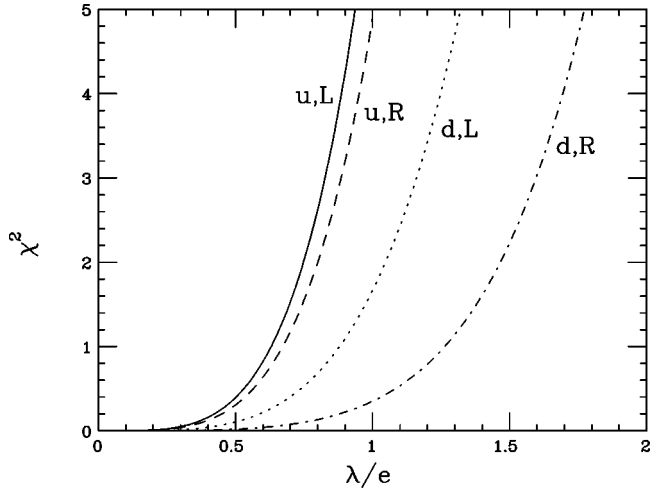

FIG. 6. χ^2 fits to Drell-Yan production including the effects of a 200 GeV scalar leptoquark for each type of leptoquark coupling as labeled. The 95% C.L. constraints are obtained when $\chi^2=3.842$.

and are responsible for the event excess observed at HERA, the Main Injector will observe them in both the pair and single production mode, and can confirm the values of the mass and coupling observed at HERA. (iii) However, since these production mechanisms are QCD processes, hadron colliders can not provide any information on the electroweak properties of leptoquarks, or on the chiralities of their couplings. The same conclusions hold for the CERN Large Hadron Colleder (LHC).

VI. CONSTRAINTS FROM PRECISION ELECTROWEAK MEASUREMENTS

With masses of only $\sim$200 GeV, which is not far above the top quark mass, one may wonder if such light leptoquarks have any influence on Z-pole precision measurements. We first examine the oblique parameters [48,49], following the conventions of Peskin and Takeuchi, and in particular the extension by Maksymyk, Burgess, and London to the enlarged parameter set S, T, U, V, W, and X. The additional parameters V, W, and X need to be included when new light particles (with masses of order the electroweak scale or less) are introduced. Since we are assuming that the various leptoquark multiplets are degenerate, apart from higher order corrections, they do not contribute to the parameter T at one loop (we recall that T is a measure of the mass splitting between the particles in a weak isospin multiplet). However, we do expect finite one-loop corrections to the other parameters, which can be straightforwardly calculated for each of the leptoquark multiplets. Here we present the results for the case of the $F=0$ type leptoquarks $\tilde{R}_{2L}$ and $R_{2L,R}$ in Fig. 7, which displays the shifts in the remaining oblique parameters as a function of the leptoquark mass. The results for the other leptoquark cases are found to be quite similar. As can be easily seen from the figure, leptoquarks in this mass range do not make appreciable contributions to the oblique parameters.

In addition to oblique corrections, it is possible that relatively light leptoquarks can lead to substantial vertex corrections, e.g., in the case of $Z\rightarrow e^+e^-$, where first generation leptoquarks and quarks may contribute in a loop. This case has been previously examined by several authors [50]. However, as shown by both Eboli *et al.* and Bhattacharyya *et al.*, the fact that first generation leptoquarks couple only to u or d quarks leads to a substantial suppression of their potential contribution to this vertex. For leptoquark masses of order 200 GeV, Yukawa couplings of order unity cannot be excluded by these considerations. We see that these constraints are much weaker than those imposed from low-energy data.

VII. e^+e^- COLLIDERS

There are several ways in which leptoquarks may make their presence known in e^+e^- collisions [51–53]. At center-of-mass energies below the threshold for pair production, the existence of leptoquarks can lead to deviations [51,53] in the cross section and angular distributions for $e^+e^-\rightarrow q\bar{q}$. This may be particularly relevant when $\sqrt{s}$ is comparable to the leptoquark mass as would be the case at LEP II if a 200 GeV leptoquark did exist. The origin of these modifications is due to the $t(u)$-channel exchange of the $F=0(2)$ leptoquark and is thus proportional in amplitude to the square of the un-

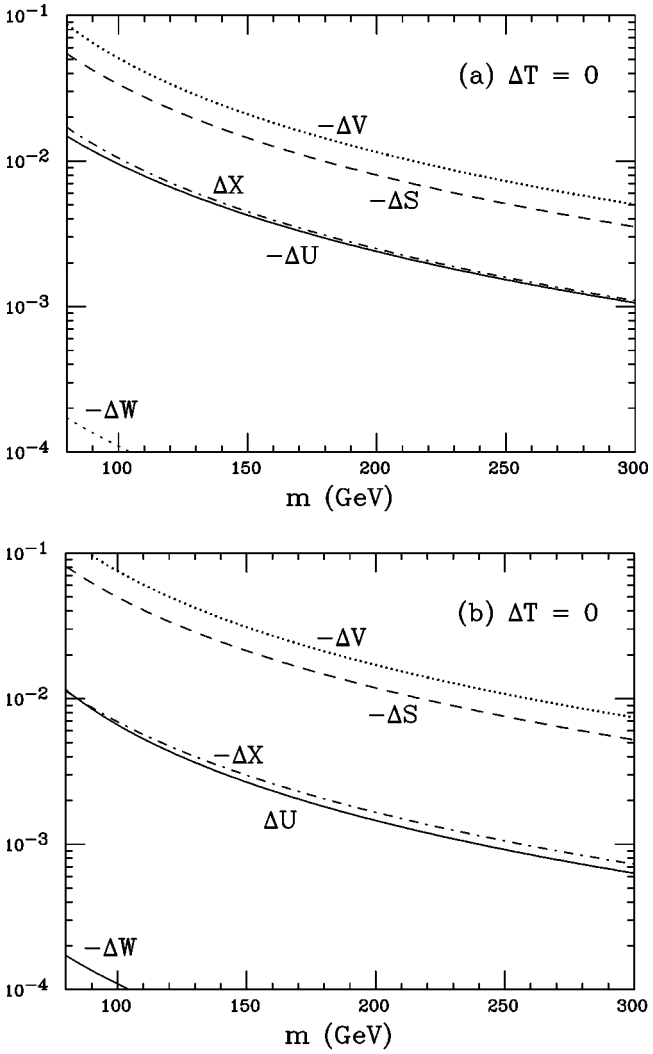

FIG. 7. Shifts in the oblique parameters as functions of the leptoquark mass for the (a) $\widetilde{R}_{2L}$ and (b) R_{2L} or R_{2R} cases.

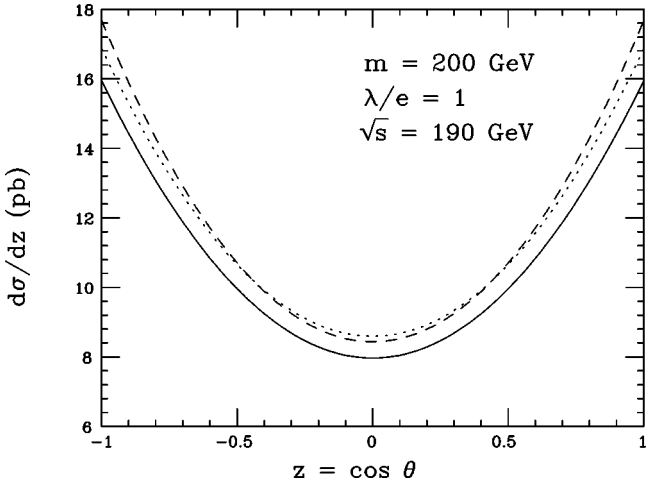

FIG. 8. Symmetrized angular distribution of $q\overline{q}$ final states in e^+e^- annihilation at 190 GeV with $z=\cos\theta$. The solid curve is for the SM while the dotted(dashed) curve includes the contribution of a 200 GeV scalar (vector) leptoquark coupling to d_L with $\widetilde{\lambda}=1$.

known Yukawa coupling. Including such terms results in the $e^+e^-\to q\overline{q}$ tree-level differential cross section given in the Appendix. Note that for first generation leptoquarks either the $u\overline{u}$ or/and $d\overline{d}$ final state may be influenced, depending on the leptoquark species being exchanged. There will be no effect on $s\overline{s}$, $c\overline{c}$, or $b\overline{b}$ final states. We now examine the sensitivity of the cross section to the value of the scaled coupling $\widetilde{\lambda}$. As an example, we consider the case of a 200 GeV leptoquark coupling to d_L with $\widetilde{\lambda}_L=1$ at LEP II with $\sqrt{s}=190$ GeV. Since d quarks cannot easily be distinguished from any of the other light flavors, nor can quarks be differentiated from antiquarks without some difficulty [54], we have symmetrized the expression in the Appendix with respect to $\cos\theta$ and summed over the possible light quark final states. Owing to this symmetrization, independent sensitivity to new t- versus u-channel exchange is lost and we can no longer distinguish $F=0$ from $F=2$ type leptoquarks. Recall that in this sample case only d_L is assumed to couple to the leptoquark, hence this flavor summation will significantly degrade the sensitivity to the Yukawa couplings in this process. Figure 8 displays the resulting angular distributions for the SM and scalar (and for completeness, vector) leptoquarks. From this it is clear that even large values of the Yukawa coupling do not lead to sizeable changes in the shape and magnitude of the cross section. Of course there is nothing special about our sample case of leptoquarks coupling to d_L and we expect modifications of a similar size when the leptoquark couples instead to d_R or $u_{L,R}$.

We now estimate the potential sensitivity of LEP II cross section measurements to nonzero values of the Yukawa coupling by generating a Monte Carlo data sample of $q\overline{q}$ events at 190 GeV with an integrated luminosity of 500 pb^{-1}. The cross section is divided into ten $\cos\theta$ bins of identical size and no additional cuts are applied. We then determine the sensitivity to the size of the Yukawa couplings assuming that only one of the quark final states couples to the leptoquark by performing a χ^2 procedure. The results of this analysis are shown in Fig. 9 for leptoquarks of either spin and for both coupling helicities to up and down quarks. For scalar leptoquarks we expect that the LEP II limits on $\widetilde{\lambda}$ will lie in the 0.5–0.8 range which is somewhat less restrictive than those that already exist due to the APV data and the $\pi\to e\nu$ decay. The expected bounds are also about a factor of 5 larger than the typical values necessary to explain the HERA excess in terms of leptoquarks. The cases where the leptoquarks are in a multiplet and can couple to both u and d quarks do not lead to any substantial improvement in these constraints when these contributions are combined. It thus appears that LEP II will be insensitive to any leptoquark consistent with the HERA data. This detailed analysis confirms the results given in the more general case examined in Djouadi *et al.* [34].

At higher energy e^+e^- colliders such as the Next Linear Collider (NLC), leptoquark pairs can be produced directly and their properties examined [51] in detail. As we will see, this allows us to easily identify which leptoquark is being produced. In what follows we again limit our discussion to the spin-0 case since it is directly relevant for the HERA events. The scalar leptoquark pair production differential cross section for this case is given by [51]

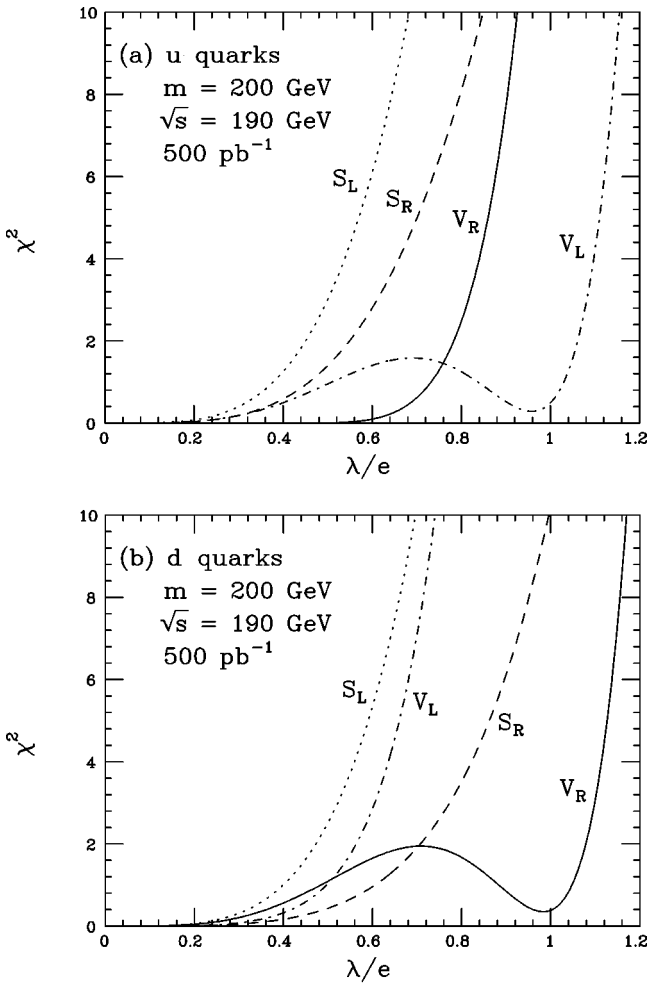

FIG. 9. χ^2 fits to the SM angular distribution for $e^+e^-\to q\overline{q}$ at 190 GeV including the effects of a 200 GeV leptoquark coupling to (a) u or (b) d quarks. In both cases the dotted(dashed) curve corresponds to a scalar leptoquark with a left(right)-handed coupling while the dash-dotted(solid) curve corresponds to the vector leptoquark case with left(right)-handed couplings. The 95% C.L. limits are obtained when $\chi^2=3.842$.

$$\frac{d\sigma}{dz}=\frac{3\pi\alpha^2}{8s}\beta^3(1-z^2)\Bigg\{2\sum_{ij}(v_e^i v_e^j+a_e^i a_e^j)C_iC_jP_{ij}-\frac{s}{t}\sum_i[\tilde{\lambda}_L^2(v_e^i+a_e^i)+\tilde{\lambda}_R^2(v_e^i-a_e^i)]C_iP_i+\frac{s^2}{4t^2}(\tilde{\lambda}_L^4+\tilde{\lambda}_R^4)\Bigg\}, \tag{18}$$

where the sum extends over γ and Z exchange, $\beta=\sqrt{1-4m^2/s}$, $C_1=Q_{LQ}$, $C_2=2[T_3-x_wQ]_{LQ}(\sqrt{2}G_FM_Z^2/4\pi\alpha)^{1/2}$, and v, a, P_{ij}, and P_i are defined in the Appendix.

When large Yukawa couplings are present, the exchange of u or d quarks in the t channel can seriously modify the pair production angular distribution away from the conventional $\sin^2\theta$ dependence leading to an appreciable forward-backward asymmetry. However, for $\tilde{\lambda}\leqslant 0.1$ this asymmetry is found to be below the 0.2% level at a $\sqrt{s}=500$ GeV collider when 200 GeV leptoquarks are being produced. Thus, in the limit that $\tilde{\lambda}\approx 0$, the cross section for a particular final state, such as $\ell\ell jj$, depends solely on the electroweak quantum numbers of the members of the relevant leptoquark multiplet and their branching fractions to charged leptons for a fixed leptoquark mass. Further information on the leptoquark electroweak quantum numbers may be obtained from examining the left-right polarization asymmetry, defined as usual as

$$A_{\ell\ell jj}^{LR}\equiv\frac{\sigma_L(\ell\ell jj)-\sigma_R(\ell\ell jj)}{\sigma_L(\ell\ell jj)+\sigma_R(\ell\ell jj)}. \tag{19}$$

TABLE V. Cross sections for the three leptoquark pair decay channels in fb at a 500 GeV NLC assuming complete leptoquark multiplets with a common mass of 200 GeV. The polarization asymmetry in the $\ell\ell jj$ channel is also given. In all cases $\tilde{\lambda}\ll 1$ is assumed.

Leptoquark	$\ell\ell jj$	$\ell\nu jj$	$\nu\nu jj$	$A_{\ell\ell jj}^{LR}$
S_{1L}	1.88	3.77	1.88	−0.618
S_{1R}	7.53	0.0	0.0	−0.618
$\widetilde{S}_{1R}$	120.4	0.0	0.0	−0.618
S_{3L}	192.2	3.77	1.88	0.931
R_{2L}	181.0	0.0	80.4	0.196
R_{2R}	261.4	0.0	0.0	−0.141
$\widetilde{R}_{2L}$	47.6	0.0	33.2	0.946

Table V summarizes the production cross sections for each final state as well as the polarization asymmetry associated with the $\ell\ell jj$ final state for all scalar leptoquark multiplets. It is clear from the table that by measuring the rates for each final state channel in addition to the polarization asymmetry that the identity of the produced leptoquark would be straightforward to obtain assuming the design luminosity of 50 fb^{-1}, as noted previously in the general analyses of Hewett and Rizzo and Blümlein *et al.* [51,55]. We note in passing that since the Yukawa couplings of the ~200 GeV LQ's are so small it is possible that LQ pair bound states can form in the mass region near 400 GeV. These states can be produced in a number of ways, such as WW fusion, and can only be explored in detail at a lepton collider such as the NLC although the lowest lying states can be produced at a hadron collider through gluon fusion.

Single leptoquark production at the NLC is also possible via $e\gamma$ collisions [56], with a production rate which is quite sensitive to the electric charge of the leptoquark. The amplitude for this process is proportional to the Yukawa coupling λ and results in a cross section which is not significantly different in magnitude from that of pair production if $\tilde{\lambda}$ is not far from unity. If both electron and photon beam polarization is available, asymmetries can also be used to determine the leptoquark's quantum numbers as has been demonstrated by Doncheski and Godfrey [56]. Table VI shows the production rate for a 200 GeV leptoquark in γe collisions at the NLC for a luminosity of 50 fb^{-1} using either the back-scattered laser or Weisacker-Williams photon spectra. In obtaining these results, the hadronic content of the photon has been ignored; its inclusion would somewhat increase these rates. The back-scattered laser approach has the advantage of a harder spectrum (although it cuts off at $x\simeq 0.84$) and both

TABLE VI. Rates for single leptoquark production in γe collisions at a 500 GeV NLC assuming complete leptoquark multiplets with a common mass of 200 GeV and an integrated luminosity of 50 fb^{-1}. In all cases $\tilde{\lambda}=0.1$ is assumed and a p_T cut on the quark jet of 10 GeV has been applied. The charged lepton branching fraction for the produced multiplet is also given.

Leptoquark	Back-scattered laser	Weisacker-Williams	B_{ℓ}
S_{1L}	212.	56.8	0.5
S_{1R}	212.	56.8	1
$\widetilde{S}_{1R}$	109.	24.4	1
S_{3L}	430.	106.	$\simeq 0.75$
R_{2L}	332.	79.5	1
R_{2R}	381.	92.6	1
$\widetilde{R}_{2L}$	49.1	13.1	1

beams can be polarized. In the Weisacker-Williams case an additional factor of 2 is included since both $\gamma e^{\pm}$ collisions are possible. Even for this small value of $\tilde{\lambda}$ the production rates are at an observable level. It is clear that by using these rates together with the use of beam polarization the quantum numbers can be determined in a straightforward manner.

VIII. UNIFICATION WITH LEPTOQUARKS

At this point one may wonder how scalar leptoquarks of the $F=0$ type would fit into a larger picture. As we saw earlier, both $R_{2L,R}$ can be embedded into a **45**, $\overline{\mathbf{45}}$ representation of SU(5) while $\widetilde{R}_{2L}$, which has less exotic electric charges, can be placed in a **10** or **15**. In a supersymmetric (SUSY) extension, where one normally adds complete multiplets to automatically insure coupling constant unification, we would thus need to add either a $\mathbf{10}+\overline{\mathbf{10}}(\mathbf{15}+\overline{\mathbf{15}})$ or a $\mathbf{45}+\overline{\mathbf{45}}$ at low energies. Here the barred representation is introduced to avoid anomalies and to guarantee that the fermionic components are vectorlike with respect to the SM gauge group. As is well known, the addition of extra matter representations delays unification and brings the GUT scale much closer to the string scale. A short analysis shows that adding complete $\mathbf{15}+\overline{\mathbf{15}}$'s or $\mathbf{45}+\overline{\mathbf{45}}$'s would lead to a dramatic loss of asymptotic freedom (AF) at one loop (i.e., $\beta_i>0$) and, in the later case, both $R_{2L,R}$ would be present in the low-energy spectrum. We would then need to explain why only one of the chiral couplings was present as well as the generational structure of the couplings by the imposition of some extra symmetries. The addition of the $\mathbf{10}+\overline{\mathbf{10}}$ to the usual MSSM particle content does not lead to either the loss of AF at one loop or to the problem of suppressing one of the chiral couplings. Interestingly, these general considerations tell us that the *only* leptoquarks consistent with both SUSY and unification within standard SU(5) are $\widetilde{R}_{2L}$ and $S_{1L,R}$ the later being the familiar leptoquarks of E_6 string-inspired models [9]. In both cases the QCD β function is found to vanish at one loop (in the E_6 case three $\mathbf{5}+\overline{\mathbf{5}}$'s are present with a different leptoquark for each generation). Since we can safely add only a single $\mathbf{10}+\overline{\mathbf{10}}$ at low energies, a realistic model would still need to explain the hierarchy of generation dependent coupling strengths. We note that in the light **10** together with the leptoquark will be a $Q=-1$ isosinglet bilepton [57] and a $Q=2/3$, color triplet, isosinglet diquark.

Although the leptoquarks in the $\mathbf{10}+\overline{\mathbf{10}}$ are found to be consistent with both unification and AF considerations, we still cannot identify them with the source of the HERA events due to the nature of their SU(5) coupling structure. To form a SU(5) singlet in the product $\bar{5}_i 5_j 10_k$, only the antisymmetric terms in the i,j can contribute. This would imply that the leptoquark must couple in an antisymmetric fashion with respect to the generations [58] so that the phenomenologically required e^+d-type coupling would be prohibited. Thus the requirements of AF, SUSY SU(5) unification, and the addition of complete multiplets do not simultaneously allow any $F=0$ leptoquarks with couplings to only a single generation.

How do we circumvent this result? One possibility is to surrender the assumption of the addition of complete SU(5) representations at low energies. This certainly allows us more flexibility at the price of naturalness but still requires us to chose subsets of $SU(3)_C\times SU(2)_L\times U(1)_Y$ representations from the **10**, **15**, or **45** which maintain AF and unification. Except for the rather bizarre choice of adding a $(2,3)(1/6)$ from a **15** and a $(1,1)(1)\oplus(1,3)(-2/3)$ from a **10** at low energy, a short analysis shows that no other solutions were found to exist. Here the notation refers to the $(SU(3)_C, SU(2)_L)(Y/2)$ quantum numbers of the representation. Thus apart from this exotic choice we find that our constraints are sufficiently strong as to disallow any $F=0$ leptoquarks at low energy in the SUSY SU(5) context.

It is clear that we must give up conventional SU(5) if we want a HERA-inspired leptoquark in a SUSY-GUT framework [59,60]. Perhaps the most attractive scenario for this is the flipped $SU(5)\times U(1)_X$ model [61] wherein the SM fermion content is extended by the addition of the right-handed neutrino ν^c and the conventional roles of u^c and e^c are interchanged with those of d^c and ν^c. Thus, u^c lies in the **5**, the d^c lies in the **10** and e^c is in an SU(5) singlet. In this case, completely different, and successful from the HERA point of view, leptoquark embeddings are now possible. For example, R_{2R} can be placed in a $\mathbf{10}+\overline{\mathbf{10}}$ without the difficulties associated with the cross generational couplings we encountered above since e^c is an SU(5) singlet. In this case we would still need to impose some additional symmetries so that R_{2R} could only couple to the first generation. Note that this $\mathbf{10}+\overline{\mathbf{10}}$ would also contain the $\widetilde{S}_{1R}$ leptoquark as well as isosinglet bilepton with $Q=1$. The $\widetilde{S}_{1R}$ may also show up as a separate resonance in e^-p collisions as discussed above if it has Yukawa couplings of order $\tilde{\lambda}\sim 0.1$ once sufficient luminosity is accumulated. R_{2L} can lie in a $\mathbf{10}+\overline{\mathbf{10}}$, but would require cross generational coupling as above since both L and u^c are in the $\overline{\mathbf{5}}$. On the other hand, $\widetilde{R}_{2L}$ now lies in a $\mathbf{45}+\overline{\mathbf{45}}$ and is excluded by the AF constraints. It thus appears that the flipped $SU(5)\times U(1)_X$ scenario provides a natural embedding for at least one of these $F=0$ leptoquarks, R_{2R}, and may predict the simultaneous existence of an $F=2$ leptoquark. Other GUT groups may provide phenomenologically successful embeddings for the other $F=0$ leptoquarks. The extension of the spectrum to include the ν^c field may

introduce some new additional interesting phenomenological implications for these leptoquarks since their interactions now extend beyond those described by the Lagrangian in Sec. II and may possibly yield excess events in the charged current channel.

If LQ's really exist in a SUSY framework then their fermionic partners, leptoquarkinos (LQ-inos) must also be observed [62]. What are the masses of such states? If the LQ-ino is lighter than the LQ then the partner will decay directly to the LQ plus the LSP, since the LQ Yukawa is so small, unless the two states are nearly degenerate. This implies that the LQ-ino is the more massive of the two states, thereby decaying into the LQ plus LSP. Since the fermion pair cross section is larger than the scalar pair cross section at the Tevatron when both are color triplet states, it is clear that the mass of the LQ-ino must be substantially heavier than 200 GeV in order to reduce the anticipated number of $eejj+\not{p}_T$ events to an acceptable level.

What can we say about these leptoquarks in the non-SUSY context? Here we can only be more speculative. As is well known, unification attempts without SUSY using only the SM particle content are doomed to failure in that they predict a too small value of the unification scale, implying a rapidly decaying proton, and lead to values of $\alpha_s(M_Z)$ which are smaller than the experimentally determined value by many standard deviations. One is led to consider the general question of whether one could add ad hoc sets of additional (non-SUSY) particles with masses at the electroweak scale to those which already exist within the SM to get unification at a higher scale and a proper value of $\alpha_s(M_Z)$ by sufficiently modifying the SM β functions. A short consideration shows that this is difficult to arrange. At one-loop, the modified β functions must satisfy the so-called ''B test'' [63]:

$$B=\frac{b_3-b_2}{b_2-b_1}=0.719\pm 0.01\pm 0.04, \tag{20}$$

where $B_{\mathrm{SUSY}}=5/7=0.714$ clearly satisfies the test. In earlier work [64], many additional particles with a wide range of strong and electroweak quantum numbers were added in many thousands of combinations in order to attempt to satisfy these constraints with only two dozen candidates surviving (see Table I in Ref. [64]). Given the higher precision of current data, at least several of these survivors could now be eliminated leaving a very short list. A survey of this list shows that there is only one case with scalars which have the correct quantum numbers to be consistent with leptoquarks of any kind. Interestingly, this case corresponds to a pair of $\widetilde{R}_{2L}$ leptoquarks with the Higgs sector of the SM augmented by an additional doublet. This scenario was first discovered in the analysis of Murayama and Yanagida [65] and is quite unique with $B=0.693$. Figure 10 shows a two-loop renormalization group (RGE) analysis of this particular case. Interestingly, for $\sin^2\theta_w(\overline{MS})=0.23165$ and $\alpha_{em}^{-1}=127.90$ we obtain $\alpha_s(M_Z)=0.123$ and a proton lifetime [66] of $10^{32\pm 1}$ yr, which is close to the present limit in the $e^+\pi^0$ mode [67].

As a final comment we note the often neglected problem of R-parity violation within a GUT context. A term in the superpotential of the form $\lambda_{ijk}5_i5_j10_k$ would generate all of the usual lepton and baryon number violating R-parity violating terms simultaneously with comparable Yukawa couplings and would lead to a very rapid proton decay. It may be possible, however, to forbid such an R-parity-violating term at the renormalizable level while having them arise as higher dimensional operators [68]. It is not clear, however, that an interaction of the type $e^c d\widetilde{u}$ can be generated in this approach with a Yukawa coupling of the right magnitude to explain the HERA events [69].

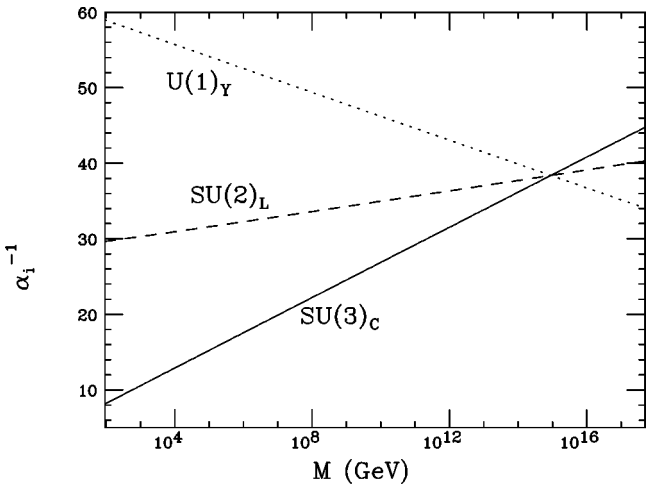

FIG. 10. Two-loop RGE evolution of the model with the SM particle content together with a pair of $\widetilde{R}_{2L}$-type leptoquarks and an additional Higgs doublet.

IX. CONCLUSIONS

In this paper we have considered the detailed phenomenological implications of interpreting the excess of events observed by both H1 and ZEUS at HERA as the production of an s-channel scalar leptoquark resonance. First, we demonstrated that the D0 leptoquark search data strongly indicate that this resonance could be neither a leptogluon nor a vector leptoquark with a mass near 200 GeV due to their much larger pair production cross sections at the Tevatron. Secondly, we showed that the HERA data itself, in particular the apparent lack of a signature in the e^-p channel even with the low accumulated luminosity, supports the idea that the leptoquark is of the $F=0$ type. We also showed that future HERA measurements in all $e^{\pm}_{L,R}p$ channels will allow a determination of the leptoquark's quantum numbers if sufficient luminosity and polarized beams become available. Thirdly, we analyzed the sensitivity of the Drell-Yan process at the Tevatron, dijet production at LEP II as well as precision electroweak measurements to the existence of leptoquarks. In all cases we found little sensitivity to leptoquarks with masses near 200 GeV with values of $\tilde{\lambda}$ near 0.1. Fourthly, we found that the single leptoquark production process at the Tevatron Main Injector may provide an independent determination of its Yukawa coupling, provided that sufficient integrated luminosity is obtainable, while pair production at the NLC allows one to directly determine all the leptoquark quantum numbers. Finally, we saw that leptoquarks can be embedded into a GUT structure both with and, surprisingly, without SUSY. Successful SUSY unification combined with the requirements of asymptotic freedom

forced us to look beyond standard SU(5) to the flipped $SU(5)\times U(1)_X$ model where R_{2R} can be embedded. Without SUSY, a model with two Higgs doublets and a pair of $\widetilde{R}_{2L}$ leptoquarks was found to unify near 10^{15} GeV and led to reasonable values for both $\alpha_s(M_Z)$ and proton lifetime. We hope that this excess of events at HERA is confirmed by enlarged data samples.

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APPENDIX: RELEVANT FORMULAS

Here we collect the relevant formulas for the processes described in the text.

Vector leptoquark single production at hadron colliders. The κ-dependent parton-level cross section for the single production of vector leptoquarks at hadron colliders is given by ($z=\cos\theta$)

$$\frac{d\sigma}{dz}=\frac{\widetilde{\lambda}^2\pi\alpha\alpha_s}{96\hat{s}}\,\beta[v_1+v_2+v_3(v_4+v_5)], \tag{A1}$$

with

$$v_1=16\left(\frac{x_2}{x_1}+\frac{x_4}{m^2}\right),$$

$$v_2=\frac{8}{(2x_4+m^2)^2}\,[a(2x_5x_6-x_4m^2)+2bx_1x_2 +2c(x_1x_6+x_2x_5-x_3x_4)-2dx_4m^2], \tag{A2}$$

$$v_3=\frac{2}{x_1(2x_4+m^2)},$$

$$v_4=32x_4x_5+16x_2x_5-16x_1x_4-32x_1x_6+16x_3x_4 -16\kappa x_1x_2,$$

$$v_5=\frac{2x_1}{m^2}\,[-2x_5x_6+(1+\kappa)(x_2x_5+x_3x_4+x_1x_6)-x_4m^2],$$

and the definitions

$$a=-1+\frac{2\kappa x_3}{m^2},\quad b=-2-2\kappa+\kappa^2,$$

$$c=2+4\kappa+\frac{(1+\kappa+\kappa^2)x_3}{m^2},\quad d=4-\frac{4x_3}{m^2}-\left[\frac{(1+\kappa)x_3}{m^2}\right]^2, \tag{A3}$$

with

$$x_1=\tfrac{1}{2}\hat{s},\quad x_2=-\tfrac{1}{2}\hat{u},$$

$$x_3=\tfrac{1}{2}(m^2-\hat{t}),\quad x_4=-\tfrac{1}{2}\hat{t},$$

$$x_5=\tfrac{1}{2}(m^2-\hat{u}),\quad x_6=\tfrac{1}{2}(\hat{s}-m^2), \tag{A4}$$

$$\hat{t}=-\tfrac{1}{2}(\hat{s}-m^2)(1+z),\quad \hat{u}=-\tfrac{1}{2}(\hat{s}-m^2)(1-z).$$

SM and leptoquark contributions to Drell-Yan production. The SM contribution to the even and odd kinematic functions are

$$F^+_{q(\mathrm{SM})}=2(1+z^2)\sum_{i,j}\,(v^i_ev^j_e+a^i_ea^j_e)(v^i_qv^j_q+a^i_qa^j_q)P_{ij}, \tag{A5}$$

$$F^-_{q(\mathrm{SM})}=4z\sum_{i,j}\,(v^i_ea^j_e+a^i_ev^j_e)(v^i_qa^j_q+a^i_qv^j_q)P_{ij},$$

where the sum extends over the γ and Z. Here we define

$$P_{ij}=\frac{\hat{s}^2[(\hat{s}-M_i^2)(\hat{s}-M_j^2)+M_i\Gamma_iM_j\Gamma_j]}{[(\hat{s}-M_i^2)^2+M_i^2\Gamma_i^2][(\hat{s}-M_j^2)^2+M_j^2\Gamma_j^2]}, \tag{A6}$$

with $M(\Gamma)$ being the masses (widths) of the gauge bosons, and the couplings are normalized as

$$v^\gamma_f=Q_f,\quad a^\gamma_f=0,$$

$$v^Z_f=\left[\frac{\sqrt{2}G_FM_Z^2}{4\pi\alpha}\right]^{1/2}(T_3-2Q_fx_w),\quad a^Z_f=\left[\frac{\sqrt{2}G_FM_Z^2}{4\pi\alpha}\right]^{1/2}T_3. \tag{A7}$$

The scalar leptoquark contributions to these kinematic functions are

$$F^+_{q(\mathrm{LQ})}=-\sum_{i=\gamma,Z}\,[(v^i_e+a^i_e)(v^i_q+a^i_q)\widetilde{\lambda}^2_{L,q}+(v^i_e-a^i_e) \times(v^i_q-a^i_q)\widetilde{\lambda}^2_{R,q}]P_i\left[\frac{\hat{t}^2}{\hat{s}(\hat{t}-m^2)}+\frac{\hat{u}^2}{\hat{s}(\hat{u}-m^2)}\right] +\frac{1}{4}\,[\widetilde{\lambda}^4_{L,q}+\widetilde{\lambda}^4_{R,q}]\left[\frac{\hat{t}^2}{(\hat{t}-m^2)^2}+\frac{\hat{u}^2}{(\hat{u}-m^2)^2}\right],$$

$$F^-_{q(\mathrm{LQ})}=\mp\sum_{i=\gamma,Z}\,[(v^i_e+a^i_e)(v^i_q+a^i_q)\widetilde{\lambda}^2_{L,q}+(v^i_e-a^i_e) \times(v^i_q-a^i_q)\widetilde{\lambda}^2_{R,q}]P_i\left[\frac{\hat{u}^2}{\hat{s}(\hat{u}-m^2)}-\frac{\hat{t}^2}{\hat{s}(\hat{t}-m^2)}\right] \pm\frac{1}{4}\,[\widetilde{\lambda}^4_{L,q}+\widetilde{\lambda}^4_{R,q}]\left[\frac{\hat{u}^2}{(\hat{u}-m^2)^2}-\frac{\hat{t}^2}{(\hat{t}-m^2)^2}\right]. \tag{A8}$$

Here,

$$P_i=\frac{s(s-M_i)}{(s-M_i^2)^2+M_i^2\Gamma_i^2}, \tag{A9}$$

and the top sign in the antisymmetric function corresponds to the $F=0$, S-type leptoquark exchange while the bottom sign is for the $F=-2$, R-type leptoquark. Here, q represents either u or d quarks, depending on the coupling structure of the exchanged leptoquark.

SM and leptoquark contributions to $e^+e^-\to q\overline{q}$.

$$\frac{d\sigma}{dz}=\frac{3\pi\alpha^2}{2s}\left\{\sum_{ij}\left[(v_e^i v_e^j+a_e^i a_e^j)(v_q^i v_q^j+a_q^i a_q^j)(1+z^2)\right.\right.$$
$$+2(v_e^i a_e^j+v_e^j a_e^i)(v_q^i a_q^j+v_q^j a_q^i)z]$$
$$-\frac{C}{2}\sum_{i=\gamma,Z}[(v_e^i+a_e^i)(v_q^i+a_q^i)\tilde{\lambda}^2_{L,q}+(v_e^i-a_e^i)$$
$$\times(v_q^i-a_q^i)\tilde{\lambda}^2_{R,q}]P_i\left[\frac{t^2}{s(t-m^2)}+\frac{u^2}{s(u-m^2)}\right.$$
$$\left.\pm\left(\frac{u^2}{s(u-m^2)}-\frac{t^2}{s(t-m^2)}\right)\right]+\frac{C}{8}[\tilde{\lambda}^4_{L,q}+\tilde{\lambda}^4_{R,q}]$$
$$\times\left[\frac{t^2}{(t-m^2)^2}+\frac{u^2}{(u-m^2)^2}\right.$$
$$\left.\left.\pm\left(\frac{u^2}{(u-m^2)^2}-\frac{t^6}{(t-m^2)^2}\right)\right]\right\}, \tag{A10}$$

with the coupling normalizations and P_{ij}, P_i as defined in Eqs. (A6), (A7), (A9), and the $\pm$ sign is for

$$\pm \quad \text{for} \quad \begin{cases} S, & (F=-2) \\ R, & (F=0). \end{cases} \tag{A11}$$

[1] See, for example, B. Schremp and F. Schremp, Phys. Lett. **153B**, 101 (1985).

[2] L. F. Abbott and E. Farhi, Phys. Lett. **101B**, 69 (1981).

[3] S. Pakvasa, Int. J. Mod. Phys. A **2**, 1317 (1987).

[4] For a review, see, K. Lane, lectures given at Theoretical Advanced Study Institute (TASI93) in Elementary Particle Physics, Boulder, CO, 1993, hep-ph/9401324.

[5] H. Georgi and S. L. Glashow, Phys. Rev. Lett. **32**, 438 (1974).

[6] J. C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974); G. Senjanovic and A. Sokorac, Z. Phys. C **20**, 255 (1983).

[7] P. H. Frampton and B.-H. Lee, Phys. Rev. Lett. **64**, 619 (1990); P. H. Frampton and T. W. Kephart, Phys. Rev. D **42**, 3892 (1990); P. H. Frampton, Mod. Phys. Lett. A **7**, 559 (1992).

[8] E. Witten, Nucl. Phys. **B258**, 75 (1985); M. Dine *et al.*, *ibid.* **B259**, 519 (1985); J. Breit, B. A. Ovrut, and G. Segre, Phys. Lett. **158B**, 33 (1985).

[9] J. L. Hewett and T. G. Rizzo, Phys. Rep. **183**, 193 (1989).

[10] H1 Collaboration, C. Adloff *et al.*, Z. Phys. C **74**, 191 (1997); ZEUS Collaboration, J. Breitweg *et al.*, *ibid.* **74**, 207 (1997).

[11] We thank J. Huston and F. Olness for discussions on this point.

[12] See, however, the discussion by S. Kuhlmann, H. L. Lai, and W. K. Tung, hep-ph/9704338, where alternative parton density parametrizations are explored.

[13] V. Barger *et al.*, hep-ph/9703311; A. E. Nelson, Phys. Rev. Lett. **78**, 4159 (1997); M. C. Gonzales-Garcia and S. F. Novaes, hep-ph/9703346; N. Di Bartolomeo and M. Fabbrichesi, hep-ph/9703375; N. G. Deshpande, B. Dutta, and X.-G. He, hep-ph/9705236.

[14] E. J. Squires, Phys. Lett. **94B**, 54 (1980); H. Harari and N. Sieberg, *ibid.* **98B**, 269 (1981); H. Fritzsch and G. Mandelbaum, *ibid.* **102B**, 319 (1981).

[15] L. E. Ibanez and G. G. Ross, Nucl. Phys. **B386**, 3 (1992).

[16] J. L. Hewett, ''Single Squark Production at HERA via R-Parity Violating Interactions,'' in *Proceedings of the 1990 Summer Study on High Energy Physics—Research Directions for the Decade*, Snowmass, CO, 1990, edited by E. L. Berger (World Scientific, Singapore, 1992).

[17] J. Butterworth and H. Dreiner, Nucl. Phys. **B397**, 3 (1993); in *Second HERA Workshop on Physics*, Hamburg, Germany, 1991, edited by W. Buchmüller and G. Ingelman (DESY, Hamburg, 1992); T. Kon and T. Kobayashi, Phys. Lett. B **270**, 81 (1991); T. Kon, T. Kobayashi, S. Kitamura, K. Nakamura, and S. Adachi, Z. Phys. C **61**, 239 (1994); T. Kon, T. Kobayashi, and S. Kitamura, Phys. Lett. B **333**, 263 (1994); Int. J. Mod. Phys. A **11**, 1875 (1996).

[18] The possibility that the HERA events can be understood within R-parity breaking or leptoquark models has been discussed by a number of authors. See, for example, H. Dreiner and P. Morawitz, hep-ph/9703279; G. Altarelli *et al.*, hep-ph/9703276; D. Choudhury and S. Raychaudhuri, Phys. Lett. B **401**, 54 (1997); Phys. Rev. D **56**, 1778 (1997); K. S. Babu, C. Kolda, J. March-Russell, and F. Wilczek, hep-ph/9703299; J. Kalinowski, R. Rückl, H. Spiesberger, and P. M. Zerwas, hep-ph/9703276; hep-ph/9703436; T. Kon and T. Kobayashi, hep-ph/9704221.

[19] W. Buchmüller, R. Rückl, and D. Wyler, Phys. Lett. B **191**, 442 (1987); see also J. Blümlein and R. Rückl, *ibid.* **304**, 337 (1993).

[20] Z. Kunszt and W. J. Stirling, hep-ph/9703427.

[21] T. Plehn, H. Spiesberger, M. Spira, and P. M. Zerwas, Z. Phys. C **74**, 611 (1997).

[22] S. Davidson, D. Bailey, and B. A. Campbell, Z. Phys. C **61**, 613 (1994); see also G. K. Leontaris and J. D. Vergados, hep-ph/9703338.

[23] M. Leurer, Phys. Rev. D **50**, 536 (1994); **49**, 333 (1994).

[24] C. S. Wood *et al.*, Science **275**, 1759 (1997).

[25] For a review see, J. L. Rosner, hep-ph/9704331.

[26] K. S. McFarland *et al.*, Report No. FNAL-Pub-97/001-E, hep-ex/9701010.

[27] C. Y. Prescott *et al.*, Phys. Lett. **84B**, 524 (1979).

[28] A. Dobado, M. J. Herrero, and C. Munoz, Phys. Lett. B **191**, 449 (1987); V. D. Angelopoulos *et al.*, Nucl. Phys. **B292**, 59 (1987); R. N. Mohapatra, G. Segre, and L. Wolfenstein, Phys. Lett. **145B**, 433 (1984); J. Blümlein, Z. Phys. C **74**, 605 (1997).

[29] J. A. Grifols and S. Peris, Phys. Lett. B **201**, 287 (1988); J. F. Gunion and E. Ma, *ibid.* **195**, 257 (1987).

[30] N. Harnew, in *Proceedings of the 1987 HERA Workshop*, Hamburg, Germany, 1987, edited by R. D. Peccei (DESY, Hamburg, 1988).

[31] For an updated discussion on the effects of QCD and initial and final state radiation, see C. Freiberg, E. Norrbin, and T. Sjöstrand, hep-ph/9704214.

[32] See, for example, A. D. Martin, R. G. Roberts, and W. J. Stirling, Phys. Lett. B **387**, 419 (1996), and references therein.
[33] J. L. Hewett and S. Pakvasa, Phys. Rev. D **37**, 3165 (1988); M. de Montigny, L. Marleau, and G. Simon, *ibid.* **52**, 533 (1995).
[34] A. Djouadi, J. Ng, and T. G. Rizzo, in *Electroweak Symmetry Breaking and Beyond the Standard Model*, edited by T. Barklow *et al.*, (World Scientific, Singapore, 1997); J. Blümlein, E. Boos, and A. Kryukov, DESY Report No. 96-174, hep-ph/9610408, and references therein (we note that these authors reproduce the scalar pair cross section as calculated in Ref. [33] which we employ here); B. Dion, L. Marleau, and G. Simon, Phys. Rev. D **56**, 479 (1997); see also P. Arnold and C. Wendt, *ibid.* **33**, 1873 (1986); G. V. Borisov, Y. F. Pirogov, and K. R. Rudakov, Z. Phys. C **36**, 217 (1987).
[35] M. de Montigny and L. Marleau, Phys. Rev. D **40**, 2869 (1989); **40**, 3616 (1989). Although the earlier expressions used by these authors for the Born cross section are incorrect, the algebraic results that they obtain for the relevant *K* factors are correct.
[36] H. L. Lai *et al.*, Phys. Rev. D **51**, 4763 (1995).
[37] M. Krämer, T. Plehn, M. Spira, and P. Zerwas, Phys. Rev. Lett. **79**, 341 (1997).
[38] D0 Collaboration, J. Hobbs, presented at the 32nd *Recontres de Moriond: Electroweak Interactions and Unified Theories*, Le Arces, France, 15-22 March, 1997 (unpublished); CDF Collaboration, K. Maeshima, in *28th International Conference on High Energy Physics*, Warsaw, Poland, 1996, Report No. FNAL-CONF-96/413-E (unpublished); CDF Collaboration, F. Abe *et al.*, Fermilab Report No. FNAL-PUB-96-450-E (unpublished).
[39] J. L. Hewett, T. G. Rizzo, S. Pakvasa, H. E. Haber, and A. Pomarol, in *Proceedings of the Workshop on Physics at Current Accelerators and the Supercollider*, 1993, edited by J. L. Hewett, A. White, and D. Zeppenfeld (ANL, Argonne, 1993), ANL-HEP-CP-93-92.
[40] J. E. Cieza Montalvo and O. J. P. Eboli, Phys. Rev. D **50**, 331 (1994).
[41] The D0 Collaboration presently quotes a lower bound of 298(270) GeV on the mass of a vector leptoquark with a charged lepton branching fraction of 1(0.5), S. Hagopian (private communication).
[42] T. G. Rizzo, Phys. Rev. D **33**, 1851 (1986); **34**, 133 (1986).
[43] U. Baur and K. H. Streng, Phys. Lett. **162B**, 387 (1985); R. S. Chivukula, M. Golden, and E. Simmons, Phys. Lett. B **257**, 403 (1991).
[44] O. J. P. Eboli and A. V. Olinto, Phys. Rev. D **38**, 173 (1988); A. Dobado, M. J. Herrero, and C. Munoz, Phys. Lett. B **207**, 97 (1988); V. Barger *et al.*, *ibid.* **220**, 464 (1989).
[45] R. Rückl and P. Zerwas, in *Proceedings of the LaThuile Workshop on Physics at Future Accelerators*, LaThuile, Italy, 1987, edited by J. H. Mulvay, CERN Report No. 87-07, 1987.
[46] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **49**, R1 (1994); Phys. Rev. Lett. **77**, 2616 (1996); D0 Collaboration, S. Abachi *et al.*, *ibid.* **75**, 1456 (1995).
[47] *Future Electroweak Physics at the Fermilab Tevatron—Report of the Tev-2000 Study Group*, edited by D. Amidei and R. Brock, Fermilab Report No. FNAL-Pub-96/082, 1996.
[48] M. Peskin and T. Takeuchi, Phys. Rev. Lett. **65**, 964 (1990); Phys. Rev. D **46**, 381 (1992); W. Marciano and J. Rosner, Phys. Rev. Lett. **65**, 2963 (1990); G. Altarelli and R. Barbieri, Phys. Lett. B **253**, 161 (1990); D. Kennedy and P. Langacker, Phys. Rev. Lett. **65**, 2967 (1990); Phys. Rev. D **44**, 1591 (1991).
[49] I. Maksymyk, C. P. Burgess, and D. London, Phys. Rev. D **50**, 529 (1994); C. P. Burgess *et al.*, Phys. Lett. B **326**, 276 (1994).
[50] O. Eboli, hep-ph/9508342; O. J. Eboli, M. C. Gonzalez-Garcia, and J. K. Mizukoshi, Phys. Lett. B **396**, 238 (1997); Nucl. Phys. **B443**, 20 (1995); G. Bhattacharyya, J. Ellis, and K. Sridhar, Phys. Lett. B **336**, 100 (1994); **338**, 522(E) (1994).
[51] J. L. Hewett and T. G. Rizzo, Phys. Rev. D **36**, 3367 (1987); J. Blümlein and R. Rückl, Phys. Lett. B **304**, 337 (1993).
[52] J. Blümlein, E. Boos, and A. Kryukov, Phys. Lett. B **392**, 150 (1997); D. Choudhury, *ibid.* **346**, 291 (1995); J. E. Cieza-Montalvo and O. J. Eboli, Phys. Rev. D **47**, 837 (1993); T. G. Rizzo, *ibid.* **44**, 186 (1991).
[53] H. Dreiner *et al.*, Mod. Phys. Lett. A **3**, 443 (1988); G. Bhattacharyya, D. Choudhury, and K. Sridhar, Phys. Lett. B **349**, 118 (1995); M. S. Berger, hep-ph/9609517.
[54] See, however, LEP/SLD Electroweak Working Group, CERN Report No. CERN-PPE/96-183, 1996 (unpublished).
[55] J. Blümlein and E. Boos, *Physics at LEP 200 and Beyond*, Proceedings of the Workshop, Teupitz, Germany, 1994, edited by T. Riemann and J. Blumlein [Nucl. Phys. B (Proc. Suppl.) **37B**, 181 (1994)].
[56] J. L. Hewett and S. Pakvasa, Phys. Lett. B **227**, 178 (1989); H. Nadeau and D. London, Phys. Rev. D **47**, 3742 (1993); O. J. Eboli *et al.*, Phys. Lett. B **311**, 147 (1993); G. Belanger, D. London, and H. Nadeau, Phys. Rev. D **49**, 3140 (1994); F. Cuypers, Nucl. Phys. **B474**, 57 (1996); T. G. Rizzo, Phys. Rev. D **44**, 186 (1991); M. A. Doncheski and S. Godfrey, *ibid.* **49**, 6220 (1994), **51**, 1040 (1995); Phys. Lett. B **393**, 355 (1997).
[57] F. Cuypers and S. Davidson, Report No. PSI-PRD-96-21, hep-ph/9609487.
[58] We would like to thank M. Worah and M. Peskin for pointing out this important observation.
[59] For a discussion of embedding leptoquarks in the Pati-Salam type unification scheme see S. F. King and G. K. Leontaris, hep-ph/9704336.
[60] For a discussion of exotic leptoquarks from string theory see J. K. Elwood and A. E. Faraggi, hep-ph/9704363.
[61] I. Antoniadis, J. Ellis, J. S. Hagelin, and D. V. Nanopolous, Phys. Lett. B **194**, 321 (1987).
[62] For an overview of the phenomenology of leptoquarkinos see Ref. [9]. See also B. Dutta, R. N. Mohapatra, and S. Nandi, hep-ph/9704428.
[63] M. Peskin (private communication).
[64] T. G. Rizzo, Phys. Rev. D **45**, 3903 (1992).
[65] H. Murayama and T. Yanagida, Mod. Phys. Lett. A **7**, 147 (1992).
[66] W. J. Marciano, talk given at the *1983 International Symposium on Lepton and Photon Interactions at High Energies*, Ithaca, NY, 1983, edited by D. G. Cassel and D. L. Kreinick, QCD161:I71:1983.
[67] Particle Data Group, R. M. Barnett *et al.*, Phys. Rev. D **54**, 1 (1996).
[68] See, for example, K. Tamvakis, Phys. Lett. B **383**, 307 (1996); **382**, 251 (1996), and references therein.
[69] See, however, the discussions in G. F. Guidice and R. Rattazzi, hep-ph/9704339; R. Barbieri, A. Strumia, and Z. Berezhiani, hep-ph/9704275.