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Much Ado About Leptoquarks: A Comprehensive Analysis *

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Abstract

We examine the phenomenological implications of a ~ 200 GeV leptoquark in light of the recent excess of events at 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 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 Tevatron are examined. While present Tevatron data most likely excludes 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 are possible in the single production channel. We investigate precision electroweak measurements as well as the process $e^+e^- \to q\bar{q}$ at 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 NLC provide the only direct mechanism to determine the leptoquark's electroweak quantum numbers.

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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 $SU(5) \times U(1)$.

1 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 (GUTs) 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 iso-spin, 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 HERA in their neutral current Deep Inelastic Scattering (DIS) data. ZEUS has collected $20.1\,\mathrm{pb}^{-1}$ of integrated luminosity in e^+p collisions and observes 5 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 2 events from the SM in this region. H1 reports 7 events in the kinematic region $M = \sqrt{xs} > 180\,\mathrm{GeV}$ and $y > 0.4$, compared to a SM prediction of 1.83 ± 0.33 with $14.19 \pm 0.32\,\mathrm{pb}^{-1}$ of integrated luminosity. Clearly, the statistical sample is too small at present to draw any conclusions and it is quite possible 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 parameterizations 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]. 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[12] in light of the HERA data, with the result that an $eeqq$ contact interaction with a right-left helicity structure and a scale of $\sim 3\,\mathrm{TeV}$ 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 $200 - 210\,\mathrm{GeV}$.

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[13]. These partiΓcles, 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

$$\mathcal{L}_{eff} = \frac{g_s}{\Lambda}\left[\lambda_L \bar{L}\sigma^{\mu\nu}\ell^a_{8,L} + \lambda_R \bar{\ell}^a_{8,R}\sigma^{\mu\nu}e_R\right] G^a_{\mu\nu}\ell + h.c.\,, \tag{1}$$

where $G^a_{\mu\nu}$ is the gluon field strength tensor, Λ is the compositeness scale, L represents the lepton doublet under $SU(2)_L$, and $\lambda_{L,R}$ parameterizes the unknown coupling. We note that this effective Lagrangian is non-renormalizable. If the chiral symmetry in these models is broken by QCD effects, the leptogluons are expected[13] to have masses or 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

$$\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k\,, \tag{2}$$

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 $SU(2)_L$ 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[14]. 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 super-partners 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. [15], and later examined in detail in Ref. [16]. The relevant terms in the interaction Lagrangian for this case are

$$\mathcal{L} = -\lambda'_{ijk}\left[\tilde{u}^j_L \bar{d}^k_R e^i_L + (\tilde{d}^k_R)^*(\bar{e}^i_L)^c u^j_L\right] + h.c. \tag{3}$$

The requirement of $SU(2)_L$ 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 stop squarks via the first term above. This case has been recently examined[17] 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 diffuclties 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.

2 What is a Leptoquark?

The interactions of leptoquarks can be described by an effective low-energy Lagrangian. The most general renormalizable $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant leptoquark-fermion interactions can be classified by their fermion number, $F = 3B + L$, and take the form[18]

$$\mathcal{L} = \mathcal{L}_{F=-2} + \mathcal{L}_{F=0}\,, \tag{4}$$

with

$$\begin{aligned}\mathcal{L}_{F=-2} &= (g_{1L}\bar{q}^c_L i\tau_2\ell_L + g_{1R}\bar{u}^c_R e_R)S_1 + \tilde{g}_{1R}\bar{d}^c_R e_R\tilde{S}_1 + g_{3L}\bar{q}^c_L i\tau_2\vec{\tau}\ell_L\vec{S}_3 \\ &\quad +(g_{2L}\bar{d}^c_R\gamma_\mu\ell_L + g_{2R}\bar{q}^c_L\gamma^\mu e_R)V_{2\mu} + \tilde{g}_{2L}\bar{u}^c_R\gamma^\mu\ell_L\tilde{V}_{2\mu} + h.c.\,, \qquad (5)\\ \mathcal{L}_{F=0} &= (h_{2L}\bar{u}_R\ell_L + h_{2R}\bar{q}_L i\tau_2 e_R)R_2 + \tilde{h}_{2L}\bar{d}_R\ell_L\tilde{R}_2 + (h_{1L}\bar{q}_L\gamma^\mu\ell_L + h_{1R}\bar{d}_R\gamma^\mu e_R)U_{1\mu} \\ &\quad +\tilde{h}_{1R}\bar{u}_R\gamma^\mu e_R\tilde{U}_{1\mu} + h_{3L}\bar{q}_L\vec{\tau}\gamma^\mu\ell_L\vec{U}_{3\mu} + h.c.\end{aligned}$$

assuming the fermionic content of the SM. Here, q_L and ℓ_L denote the $SU(2)_L$ 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 $SU(2)_L$ 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 rapid proton decay. Note that the leptoquarks with fermion number (F) of -2 (S and V) couple to ℓq, while the $F=0$ leptoquarks (R and U) have $\ell\bar{q}$ couplings. Once this effective Langrangian is specified, the gauge couplings of the leptoquarks are completely determined. Thus, only the strength of the leptoquark's fermionic Yukawa coupling remains unknown. For calculational purposes, these couplings are generally scaled to the electromagnetic coupling,

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

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 1 for each leptoquark species. 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 $\overline{LQ}_{F=0} \to \ell \bar{q}$. 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, 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 $SU(15)$, which contains all 14 possible leptoquark states!

Using Eq. 6, the total leptoquark decay widths are easily calculated to be

$$\Gamma = \begin{array}{ll} \frac{\alpha m_{LQ}}{4} \sum_i \tilde{\lambda}_i^2 = 0.386 \, \frac{m}{200\,\mathrm{GeV}} \sum_i \tilde{\lambda}_i^2 \,\mathrm{GeV}\,, & \text{Scalars} \\ \frac{\alpha m_{LQ}}{6} \sum_i \tilde{\lambda}_i^2 = 0.258 \, \frac{m}{200\,\mathrm{GeV}} \sum_i \tilde{\lambda}_i^2 \,\mathrm{GeV}\,, & \text{Vectors}\,, \end{array} \tag{7}$$

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 long-lived, especially for the values of $\tilde{\lambda}$ that are consistent with the low-energy constraints discussed in the next section.

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

Table 1: Quantum numbers and fermionic coupling of the leptoquark states. No distinction is made between the representation and its conjugate.

3 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

$$\mathcal{L} = \frac{\lambda_L\lambda_R}{2m^2_{LQ}}\bar{u}_R d_L \bar{e}_R \nu_L \,, \tag{8}$$

which gives a large contribution to the decay $\pi^+ \to e^+\bar{\nu}_e$. Comparison with current data results[19, 20] 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[19] $M_{LQ} > 1000\lambda_L\lambda_R$ TeV, and again we see that these couplings must be 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[19], 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 can 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[20] and also by Davidson *et al.*[19] for both cases of scalar and vector leptoquarks. We summarize these results in Table 2. Note that these bounds are far from trivial. For example, we see from this Table that a spin-0, $\tilde{R}_{2L}$ leptoquark with a mass of 200 GeV must have $\tilde{\lambda} < 0.31$! As we will see below this is not far from the value suggested by the excess of events at HERA.

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[21] we obtain the constraint $\tilde{\lambda}_{iL,R} \lesssim 0.4 - 0.6$ for 200 GeV leptoquarks. NuTeV[21] may be able to improve this reach by a factor of two. Older results, such as that from the SLAC polarized electron-Deuteron scattering experiment[22], are only sensitive to $\tilde{\lambda}_{iL,R}$ of order unity or greater.

Leptoquark	Limit	Leptoquark	Limit
S_{1L}	1040	U_{1L}	1300
S_{1R}	600	U_{1R}	460
$\widetilde{S}_{1R}$	630	$\widetilde{U}_{1R}$	430
S_{3L}	550	U_{3L}	1500
R_{2L}	440	V_{2L}	460
R_{2R}	600	V_{2R}	430
$\widetilde{R}_{2L}$	630	$\widetilde{V}_{2L}$	1500

Table 2: Combined limits on the ratio $m/\tilde{\lambda}$ in GeV, where m is the leptoquark mass, for the leptoquarks multiplets from data on Atomic Parity Violation and the decay $\pi \to e\nu$.

4 Leptoquarks at HERA

Clearly, ep collisions are especially well suited for leptoquark production and offer striking signals. Direct production contributes to DIS in either the neutral or charged current channel, through an s-channel resonance $e^{\pm}\ \overset{(-)}{q} \to LQ$ with the subsequent decay to either $e^{\pm}\ \overset{(-)}{q}$ or $\nu_e\ \overset{(-)}{q}$ 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[23]. 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 ($\bar{q}$) partons. For example, the $F = -2$ leptoquarks (S and V) mediate DIS through the s-channel (u-channel) in $e^+\bar{q}$ (e^+q) collisions, while the $F = 0$ states are exchanged in the u-channel (s-channel) in $e^+\bar{q}$ (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 $\sim 200\,\mathrm{GeV}$ vector leptoquarks are most likely excluded by Tevatron data as shown in the next section. In this case, the cross section is dominated by the s-channel resonance, and the narrow width of these states, as seen as Eq. 7 justifies the use of the narrow width approximation. The differential cross section for leptoquark production can then be written as

$$\frac{d\sigma(ep\to LQ\to ej)}{dy}=\frac{\pi^2\alpha}{s}\tilde{\lambda}^2\;{}^{(}\bar{q}^{)}(m^2/s,Q^2)B_\ell\left\{\begin{array}{cc}1\,, & \text{Scalar}\\ 6(1-y)^2\,, & \text{Vector}\end{array}\right\}. \tag{9}$$

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

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

with the range $0.25\le y\le 1.0$, and employ the MRSA' distributions[24]. The resulting expected excess of events from scalar leptoquark production are displayed in Table 3 for e^+p and e^-p collisions, scaled to $20\,\mathrm{pb}^{-1}$ and $1\,\mathrm{pb}^{-1}$ of integrated luminosity, respectively. Here we assume $m=200\,\mathrm{GeV}$ and for purposes of demonstration $\tilde{\lambda}=0.1$. The numbers in brackets represent the corresponding event rate in the $\not{p}_Tj$ channel. Note that only 2 leptoquark species can contribute to charged current DIS. 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

Leptoquark	$N_{e^+}(20\,\mathrm{pb}^{-1})$	$N_{e^-}(1\,\mathrm{pb}^{-1})$
S_{1L}	0.054 (0.054)	0.591 (0.591)
S_{1R}	0.108	1.18
$\tilde{S}_{1R}$	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
$\tilde{R}_{2L}$	5.58	0.012

Table 3: Number of events for scalar leptoquark production in e^+p and e^-p collisions, scaled to $20\,\mathrm{pb}^{-1}$ and $1\,\mathrm{pb}^{-1}$ of integrated luminosity, respectively, assuming $m = 200$ GeV, $\lambda = 0.1e$, and taking $0.25 \leq y \leq 1.0$. The numbers in brackets indicate the corresponding expected event yield in the charged current channel.

excess of events in the $\sim 1\,\mathrm{pb}^{-1}$ 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 600 excess events in $1\,\mathrm{pb}^{-1}$ 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 $\tilde{R}_{2L}$, the predicted number of events in the e^+j channel with the assumed coupling strength of $\tilde{\lambda} \simeq 0.1$ is consistent with the data, while for $R_{2L,R}$ the coupling would have to be somewhat smaller, with $\tilde{\lambda} \sim 0.03 - 0.04$.

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[18, 25]. (It is expected that polarization levels of $P \approx 50\%$ may be achievable at HERA in the future.) Table 4 displays the total number of expected events, scaled to $100\,\mathrm{pb}^{-1}$, assuming

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

Table 4: Number of events per $100^{-1}pb$ for each electron charge and state of polarization for a 200 GeV scalar leptoquark at HERA assuming $0.4 < y < 1$, $\tilde{\lambda} = 0.1$, and $M_{ej} = 200 \pm 20$ GeV. These results have been smeared with a detector resolution of 5% in M_{ej}.

100% beam polarization for $e^{\pm}_{L,R}p$ collisions for a 200 GeV scalar leptoquark of each type, subject to the cuts $0.4 \leq y \leq 1.0$ and $M_{ej} = 200 \pm 20\,\mathrm{GeV}$ to remove the SM background. 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 in the four channels will allow the leptoquark quantum numbers to be determined if sufficient statistics are available.

5 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[26, 27] 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 $q\bar{q} \to LQ\overline{LQ}$ with t-channel lepton exchange, however this contribution is negligible for the size of Yukawa couplings of relevance here, $\lambda \sim \mathcal{O}(10^{-1}e)$. The pair production of scalar leptoquarks thus mimics that of squarks. The 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 MSRA' parton distributions[24], and omitted the K-factor which has been calculated[28] 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. We note that the cross section falls rapidly, dropping by a factor of 1.32 between $m = 200$ and $210\,\mathrm{GeV}$ with $\sigma(m = 210\,\mathrm{GeV}) = 0.089$ pb (including the K-factor).

The signatures for leptoquark pair production are 2 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 CDF has searched in the dilepton+dijet case for all three lepton generations. For each generational coupling the most stringent bounds[29] are $m_{(e)} > 175$ 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 $\sigma \lesssim 0.25\ \mathrm{pb}^{-1}$. This D0 bound is based on the observation of 3 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 representations which contribute to the cross section significantly more than that of a single leptoquark, *e.g.*, R_{2L}, will have a more difficult time satisfying this constraint. We stress again that these bounds 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 $110pb^{-1}$. Based on our cross section above, we would expect CDF to observe at most 1 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 200 GeV.

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 case various anomalous gVV and $ggVV$ couplings could be present, one of which can be described by an anomalous chromo-magnetic moment, κ. This term represents the only dimension 4 anomalous coupling which conserves CP. In gauge theories κ takes on the value of unity. The cross sections for vector leptoquarks with $\kappa = 1$ have been computed in Refs. [27, 30, 31]. In this case the total event rate, scaled again to $100\,\mathrm{pb}^{-1}$ of integrated luminosity, for VV production at the Tevatron is given by the dashed curve in Fig. 1. 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. 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. Clearly, the experiments themselves need to perform a detailed analysis in order to confirm this estimate.

The results in the more general case[27, 30] of $\kappa \neq 0$ are displayed in Fig. 2. 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 $\sigma_{low} \approx 0.6$ 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 larger than the D0 bound[29] of 0.25 pb and would exclude 200 GeV vector leptoquarks for this κ with $B_\ell = 1$. 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.

Here, we also consider the case of pair production of leptogluons at the Tevatron. This process was considered in Refs. [32, 33] 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 $100\,\mathrm{pb}^{-1}$, 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.

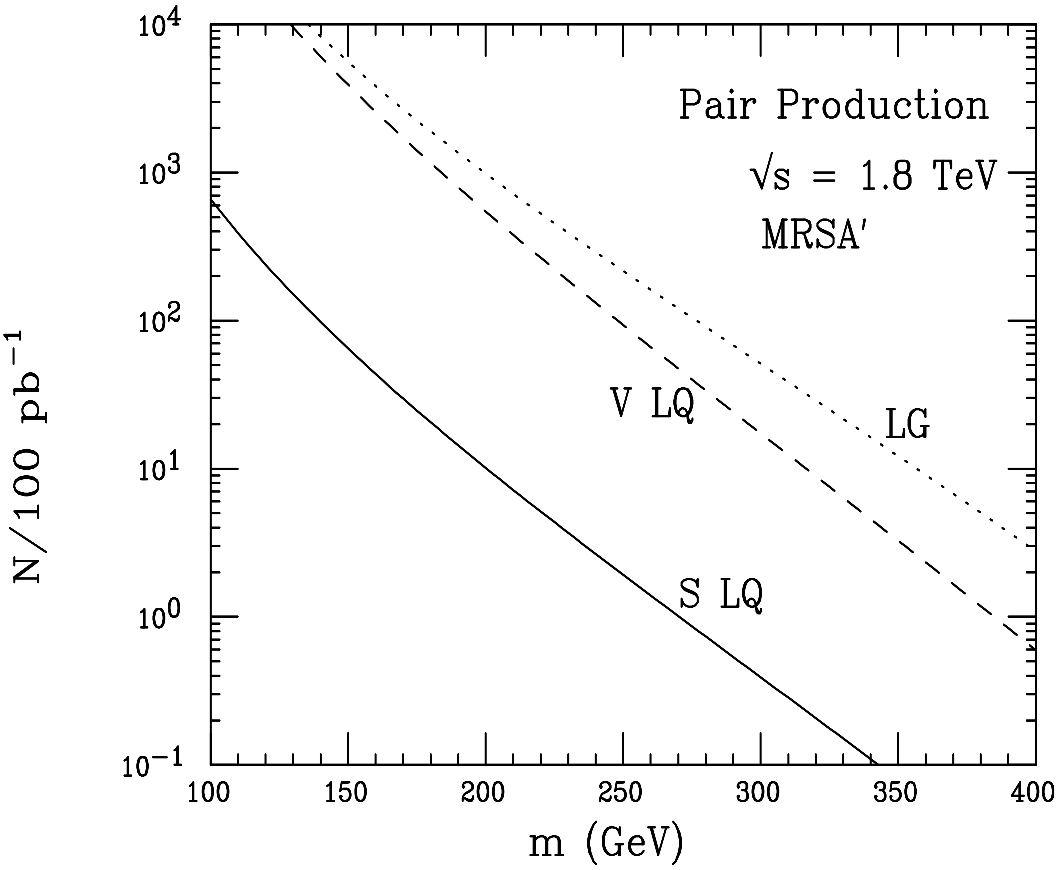


Figure 1: Pair production cross sections at the Tevatron for scalar and vector leptoquarks, as well as leptogluons, corresponding to the solid, dashed, and dotted curves, respectively. Here, the gg and $q\bar{q}$ contributions are summed.

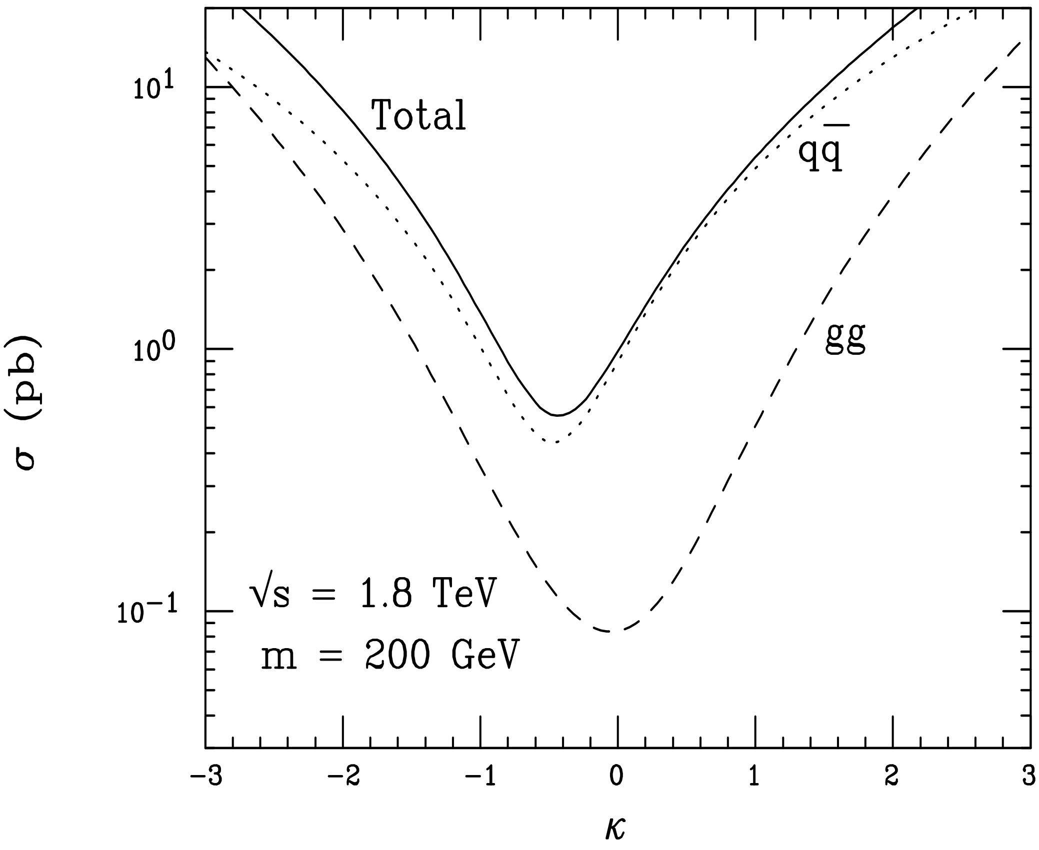


Figure 2: κ dependence of the $q\bar{q}$, gg, and total vector leptoquark pair production cross sections at the Tevatron, represented by the dotted, dashed, and solid curves, respectively. The leptoquark mass is taken to be 200 GeV.

Leptoquarks can also be produced singly at hadron colliders. The parton level subprocess responsible for single production is $qg \to LQ + \ell$, 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[26, 34]

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

where $\hat{t} = \frac{1}{2}(m^2 - \hat{s})(1-\cos\theta)$ 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 (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 $\bar{p}p$ 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[28]), which enhances the cross section by a factor of 1.25. For a 200 GeV scalar leptoquark with coupling strength of order $\lambda/e = 0.1$, our results show that $\sim 100, 300$ events from $gd + g\bar{d}$, $gu + g\bar{u}$ fusion, respectively, would be obtained with 1 fb^{-1} of integrated luminosity at the Main Injector. This event rate should be sufficient to provide a rough determination of the value of 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[35]. 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

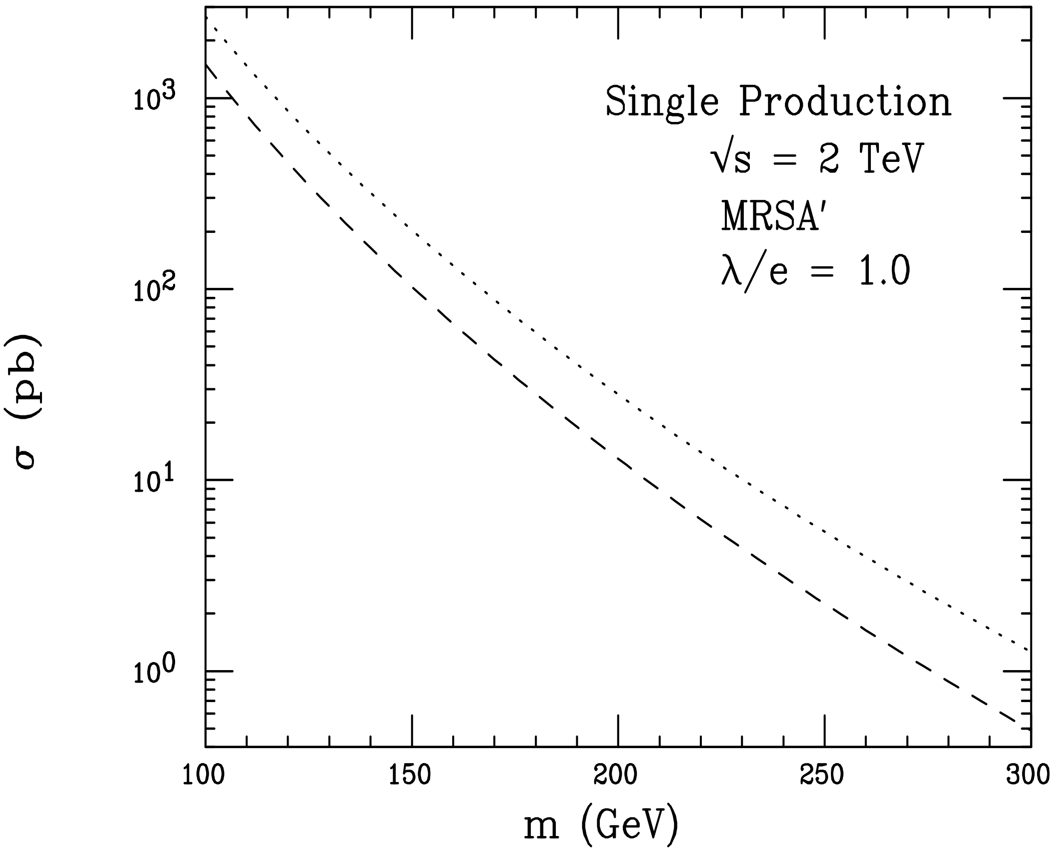


Figure 3: Single production cross sections at the Tevatron for scalar leptoquarks as a function of mass from $gu(\bar{u})$ and $gd(\bar{d})$ fusion, corresponding to the dotted and dashed curves, respectively. Here, $\lambda/e = 1$, and the K-factor has been omitted.

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

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

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 integrated over the regions $-Y \le y \le Y$ and $-Z \le z \le Z$ where

$$\begin{aligned} Y &= min[y_{max}, -ln(M/\sqrt{s})] \,, \\ Z &= min[\tanh(Y - |y|), 1] \end{aligned} \tag{14}$$

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 $|z| \le |Z|$) and then over y; the difference of the forward and backward cross sections divided by their sum then gives A_{FB}. Explicitly, we define

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

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

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

Figure 4 displays our results for (a) the Drell-Yan invariant mass spectrum and (b) forward-backward asymmetry in tГhe 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[36], $|y_{max}| \leq 1$. 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 in 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 $\sqrt{s} = 2\,\text{TeV}$. Following Ref. [37], we enlarge the rapidity coverage to $|Y| < 2.5$ and construct 21 invariant mass bins, corresponding to

$$\begin{array}{rcl}
\text{4 bins in steps of 10 GeV in the range} & 40 \leq M \leq 80 & \text{GeV}\,, \\
\text{5 bins in steps of 4 GeV in the range} & 80 \leq M \leq 100 & \text{GeV}\,, \\
\text{5 bins in steps of 20 GeV in the range} & 100 \leq M \leq 200 & \text{GeV}\,, \\
\text{5 bins in steps of 40 GeV in the range} & 200 \leq M \leq 400 & \text{GeV}\,, \\
\text{2 bins in steps of 100 GeV in the range} & 400 \leq M \leq 600 & \text{GeV}\,.
\end{array} \tag{17}$$

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

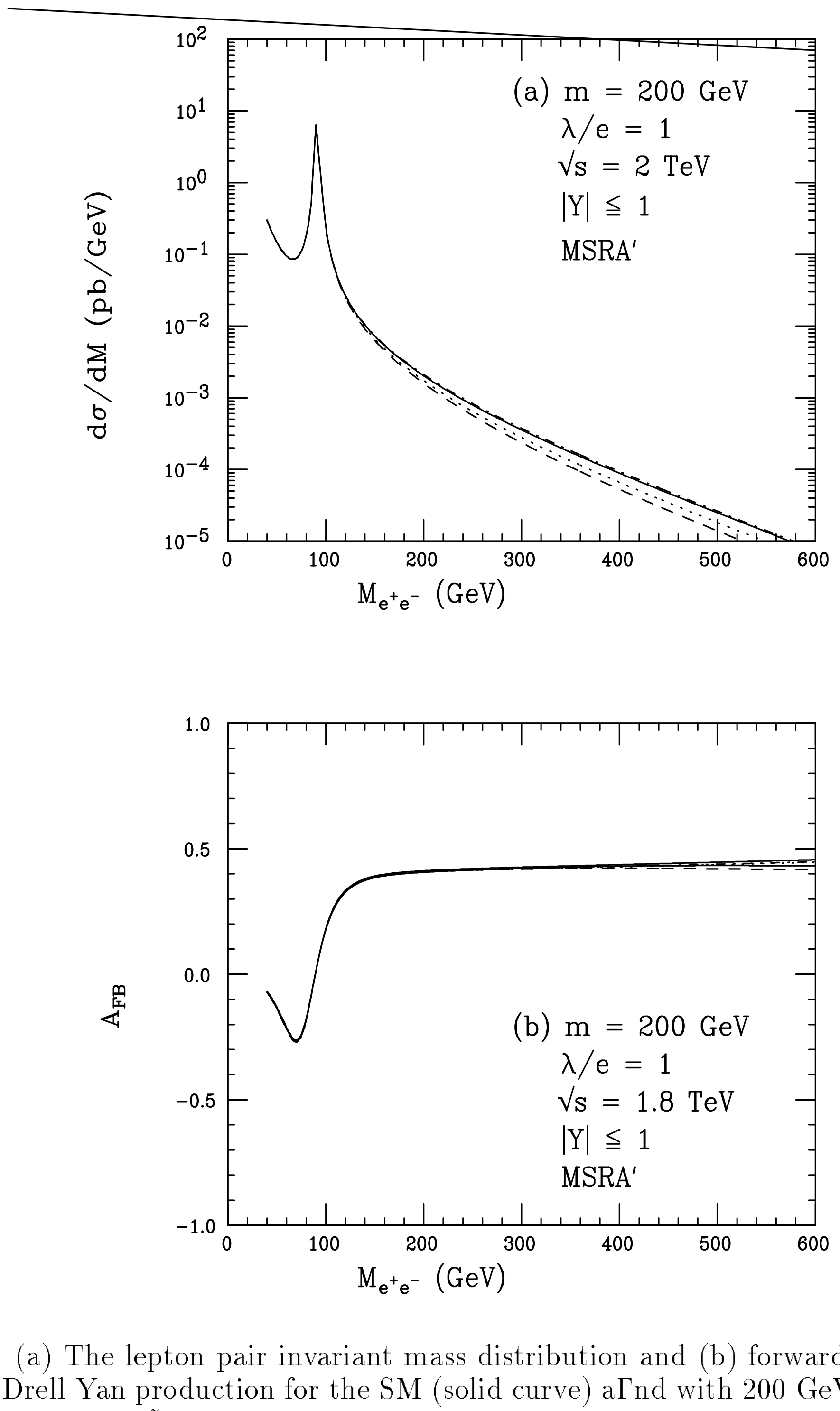


Figure 4: (a) The lepton pair invariant mass distribution and (b) forward-backward asymmetry in Drell-Yan production for the SM (solid curve) aΓnd with 200 GeV scalar leptoquark exchange, assuming $\tilde{\lambda} = 1$, with left-(right-)handed couplings to u-quarks, corresponding to the dashed (dotted)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

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,

$$\chi_i^2 = \sum_{\rm bins} \left(\frac{Q_i - Q_i^{SM}}{\delta Q_i} \right)^2 , \tag{18}$$

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, 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 LHC.

6 Constraints from Precision Electroweak Measurements

With masses of only ~ 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[38, 39], following the conventions of Peskin and Takeuchi,

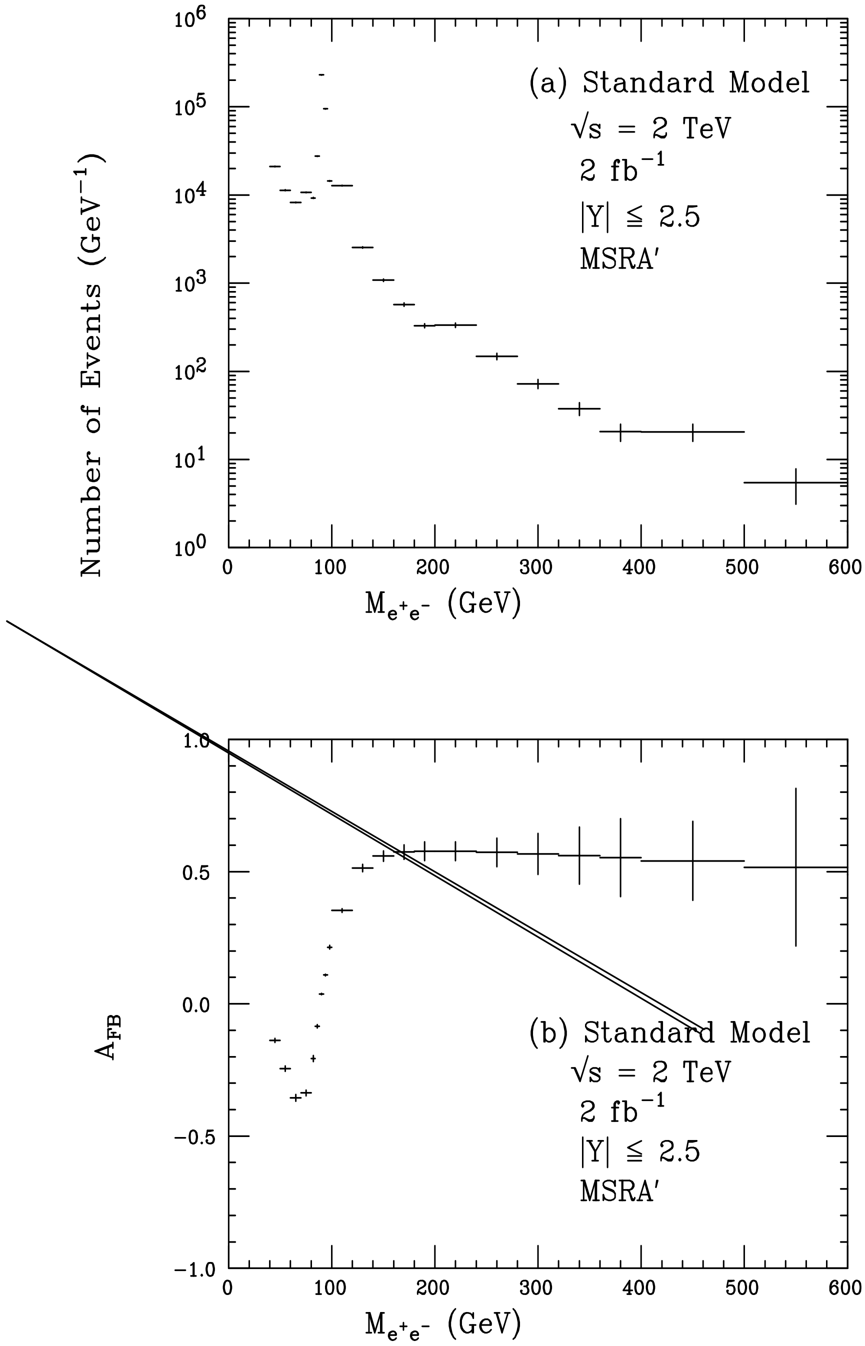


Figure 5: Bin integrated lepton pair (a) invariant mass distribution and (b) forward-backward asymmetry for Drell-Yan production in the SM at the Main Injector. The vertical lines correspond to the expected statistical error in each bin.

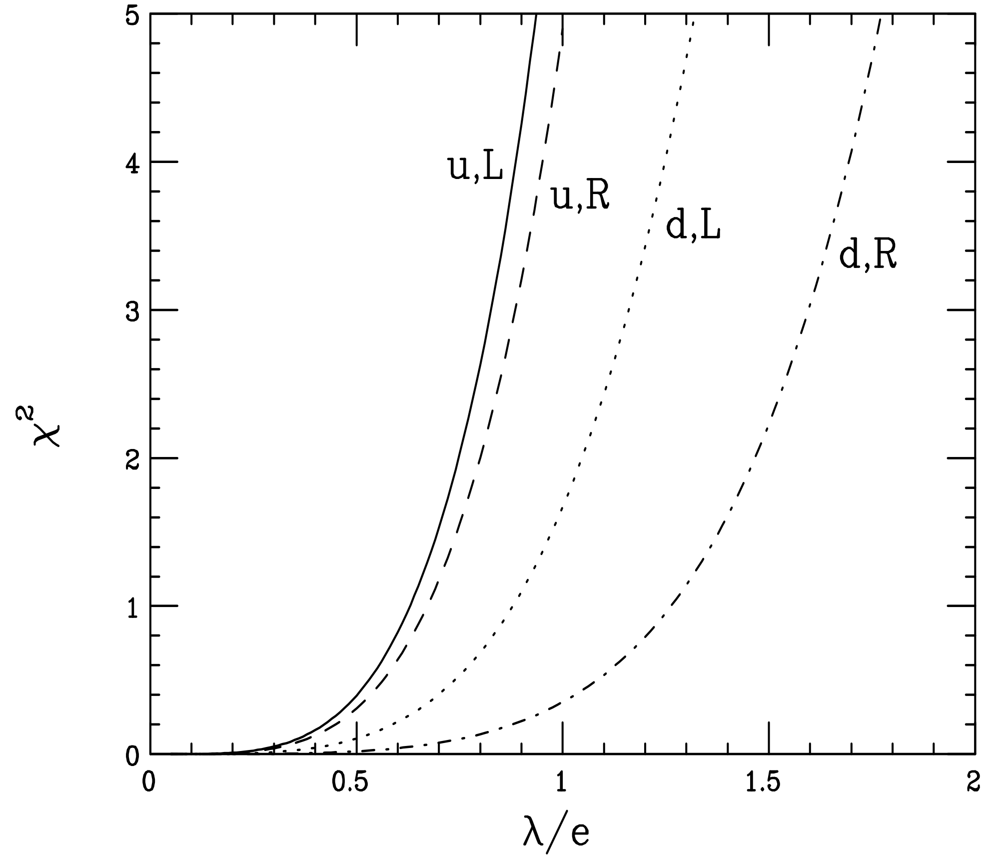


Figure 6: χ^2 fits to Drell-Yan production including the effects of a 200 GeV scalar leptoquark for each type of leptoquark coupling as labeled. The 95% C.L. constraints are obtained when $\chi^2 = 3.842$.

and 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 sample case of $\widetilde{R}_{2L}$ 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 $Z \to e^+e^-$, where first generation leptoquarks and quarks may contribute in a loop. This case has been previously examined by several authors[40]. 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.

7 e^+e^- Colliders

There are several ways in which leptoquarks may make their presence known in e^+e^- collisions[41, 42, 43]. At center of mass energies below the threshold for pair production,

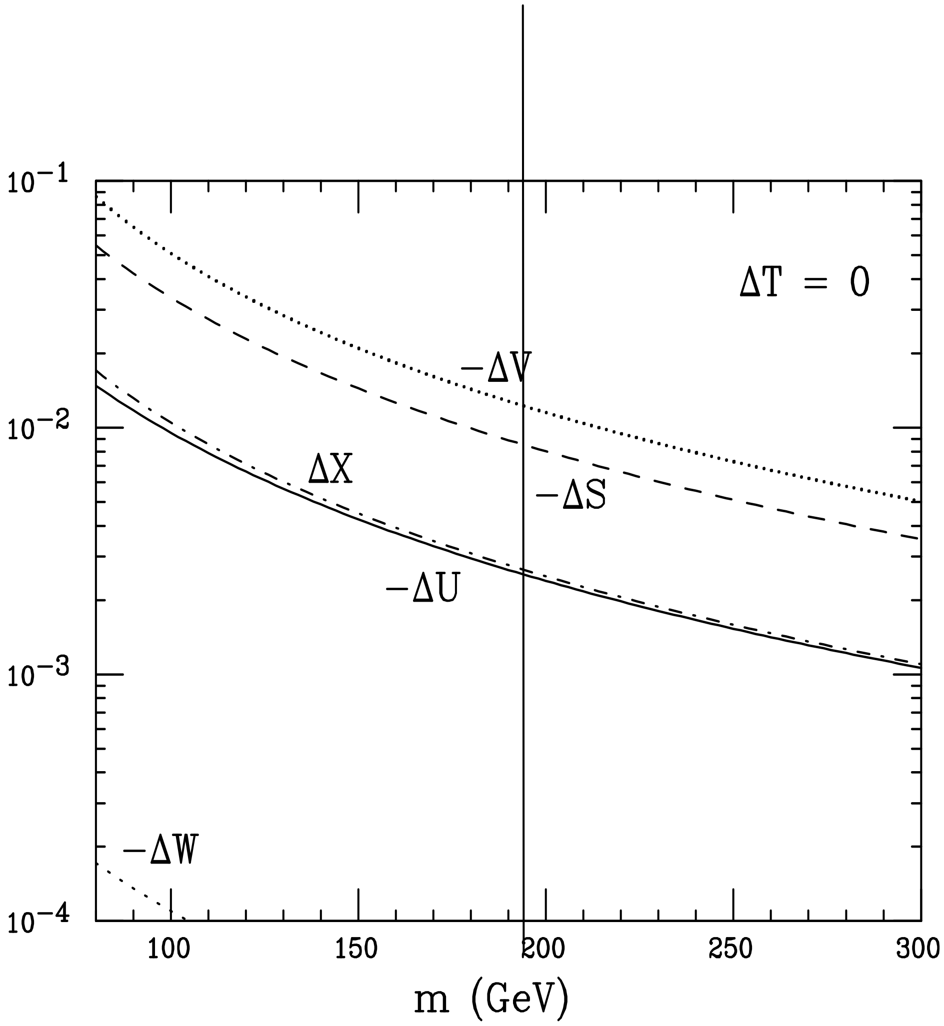


Figure 7: Shifts in the oblique parameters as functions of the leptoquark mass for the $\widetilde{R}_{2L}$ case.

the existence of leptoquarks can lead to deviations[41, 43] in the cross section and angular distributions for $e^+e^- \to q\bar{q}$. 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 unknown Yukawa coupling. Including such terms results in the $e^+e^- \to q\bar{q}$ tree-level differential cross section given in the Appendix. Note that for first generation leptoquarks either the $u\bar{u}$ or/and $d\bar{d}$ final state may be influenced, depending on the leptoquark species being exchanged. There will be no effect on $s\bar{s}$, $c\bar{c}$ or $b\bar{b}$ final states. We now examine the sensitivity of the cross section to the value of the scaled coupling $\tilde{\lambda}$. As an example, we consider the case of a 200 GeV leptoquark coupling to d_L with $\tilde{\lambda}_L = 1$ 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[44], 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 size 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 non-zero values of the Yukawa coupling by generating a Monte Carlo data sample of $q\bar{q}$

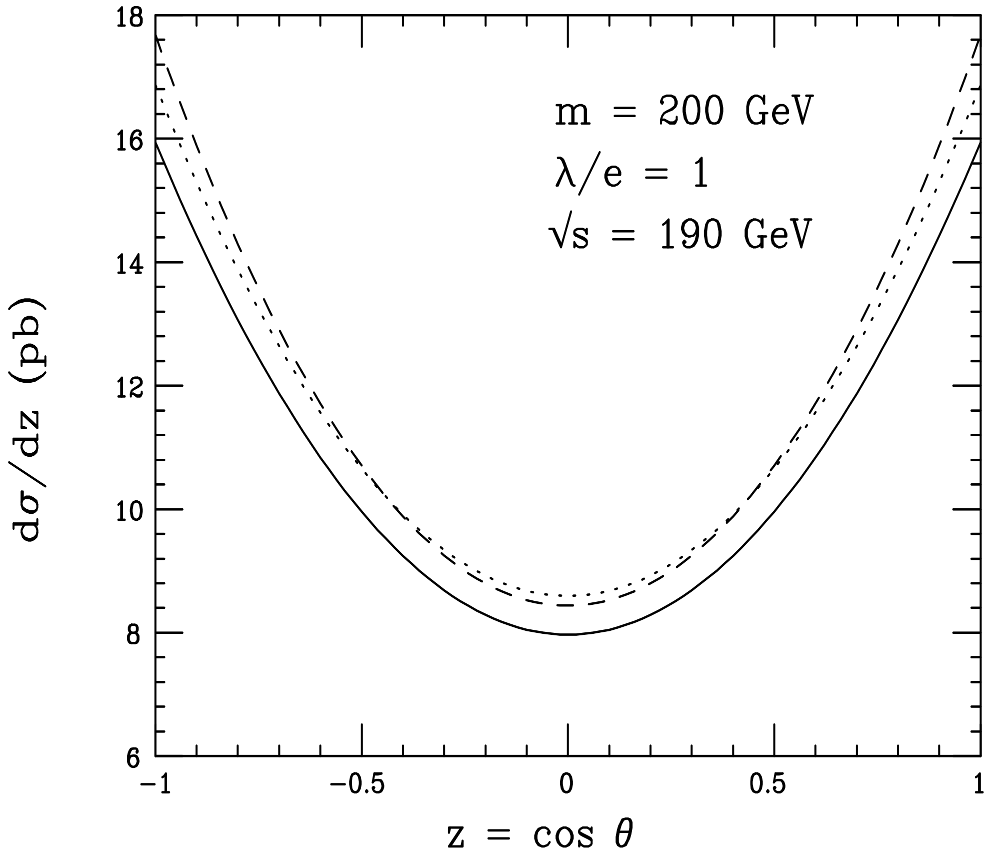


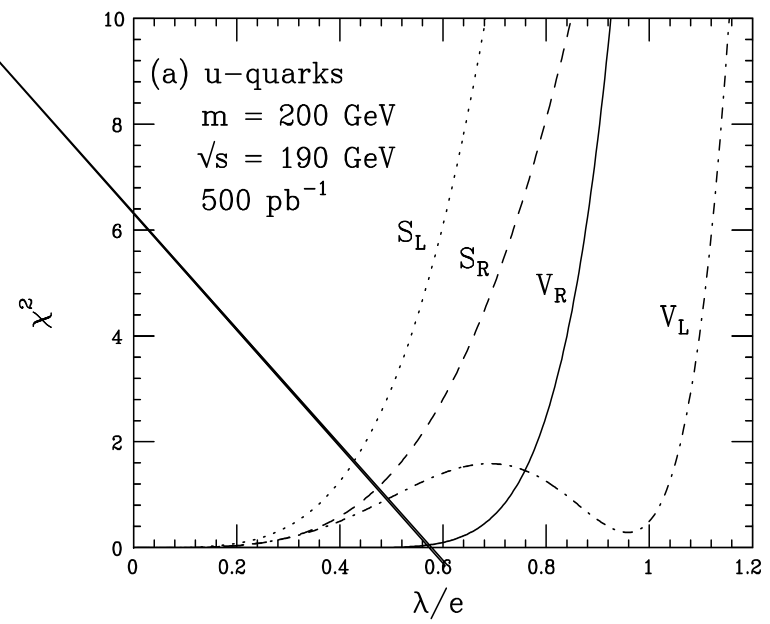
Figure 8: Symmetrized angular distribution of $q\bar{q}$ final states in e^+e^- annihilation at 190 GeV with $z = \cos\theta$. The solid curve is for the SM while the dotted(dashed) curve includes the contribution of a 200 GeV scalar(vector) leptoquark coupling to d_L with $\tilde{\lambda} = 1$.

events at 190 GeV with an integrated luminosity of $500\,\mathrm{pb}^{-1}$. The cross section is divided into 10 $\cos\theta$ 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 $\tilde{\lambda}$ 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.

At higher energy e^+e^- colliders such as the NLC, leptoquark pairs can be produced directly and their properties examined[41] 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 pair production differential cross section is given by

$$\begin{aligned}
\frac{d\sigma}{dz} &= \frac{3\pi\alpha^2}{8s}\beta^3(1-z^2)\left\{2\sum_{ij}(v_e^i v_e^j + a_e^i a_e^j)C_i C_j P_{ij}\right. \\
&\left. -\frac{s}{t}\sum_i\left[\tilde{\lambda}_L^2(v_e^i + a_e^i) + \tilde{\lambda}_R^2(v_e^i - a_e^i)\right]C_i P_i + \frac{s^2}{4t^2}(\tilde{\lambda}_L^4 + \tilde{\lambda}_R^4)\right\}\,,
\end{aligned} \tag{19}$$

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



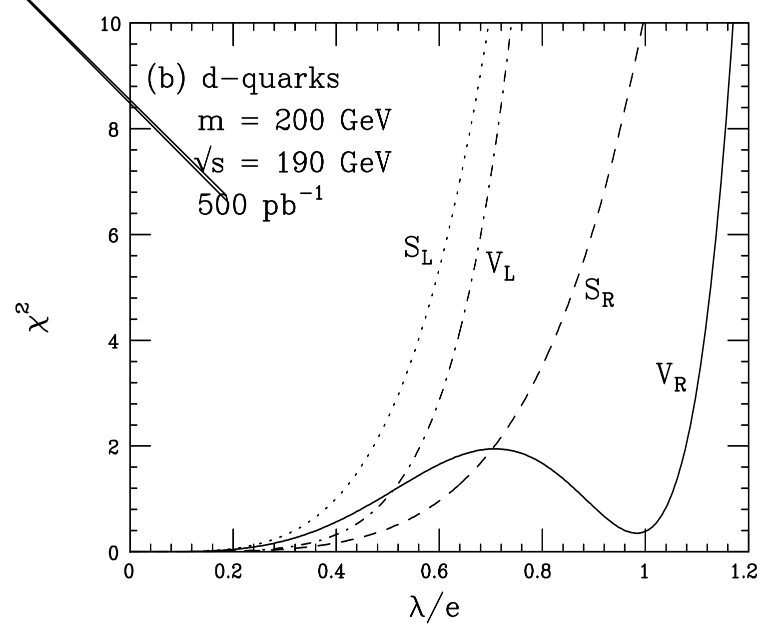


Figure 9: χ^2 fits to the SM angular distribution for $e^+e^- \to q\bar{q}$ at 190 GeV including the effects of a 200 GeV leptoquark coupling to (a) u- or (b) d-quarks. In both cases the dotted(dashed) curve corresponds to a scalar leptoquark with a left(right)-handed coupling while the dash-dotted(solid)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

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 $\tilde{\lambda} \leq 0.1$ 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

$$A^{LR}_{\ell\ell jj} \equiv \frac{\sigma_L(\ell\ell jj) - \sigma_R(\ell\ell jj)}{\sigma_L(\ell\ell jj) + \sigma_R(\ell\ell jj)}\,. \tag{20}$$

Table 5 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 $50 fb^{-1}$.

Single leptoquark production at the NLC is also possible via eγ collisions[45], 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 than that of pair production. If polarized beams are available, it can also be used to determined the leptoquark's quantum numbers.

Leptoquark	$\ell\ell jj$	$\ell\nu jj$	$\nu\nu jj$	$A^{LR}_{\ell\ell jj}$
S_{1L}	1.88	3.77	1.88	-0.618
S_{1R}	7.53	0.0	0.0	-0.618
$\tilde{S}_{1R}$	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
$\tilde{R}_{2L}$	47.6	0.0	33.2	0.946

Table 5: 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.

8 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 $\tilde{R}_{2L}$, which has less exotic electric charges, can be placed in a **10** or **15**. In a 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 vector-like with respect to the SM gauge group. A short analysis shows that adding complete $\mathbf{15}+\overline{\mathbf{15}}$'s or $\mathbf{45}+\overline{\mathbf{45}}$'s would lead to a 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 $SU(5)$ 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 beta-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 $\mathbf{10}$ together with the leptoquark will be a $Q=-1$ isosinglet bilepton[46] 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 $\bar{5}_i\bar{5}_j 10_k$, 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[47] 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 $\mathbf{10}$, $\mathbf{15}$ or $\mathbf{45}$ which maintain AF and unification. Except for the rather bizarre choice of adding a $(2,3)(1/6)$ from $\mathbf{15}$ and a $(1,1)(1) \oplus (1,\bar{3})(-2/3)$ from a $\mathbf{10}$ at low energy, no other solution was 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 $SU(5)$ if we want a HERA-inspired leptoquark in a SUSY-GUT framework. Perhaps the most attractive scenario for this is the flipped $SU(5) \times U(1)_X$ model[48] wherein the SM fermion content is extended by 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 $\overline{\mathbf{5}}$, the d^c lies in the $\mathbf{10}$ 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 an 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 otherhand, $\widetilde{R}_{2L}$ 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 Section 2.

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 beta functions. A short consideration shows that this is difficult to arrange. At one-loop, the modified beta functions must satisfy the so-called "B-test"[49]:

$$B = \frac{b_3 - b_2}{b_2 - b_1} = 0.719 \pm 0.01 \pm 0.04\,, \tag{21}$$

where $B_{SUSY} = 5/7 = 0.714$ clearly satisfies the test. In earlier work[50], 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 1 in Ref.[50]). 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 $\tilde{R}_{2L}$ 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[51] 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[52] of $10^{32\pm 1}$ yrs, which is close to the present limit in the $e^+\pi^0$ mode[53].

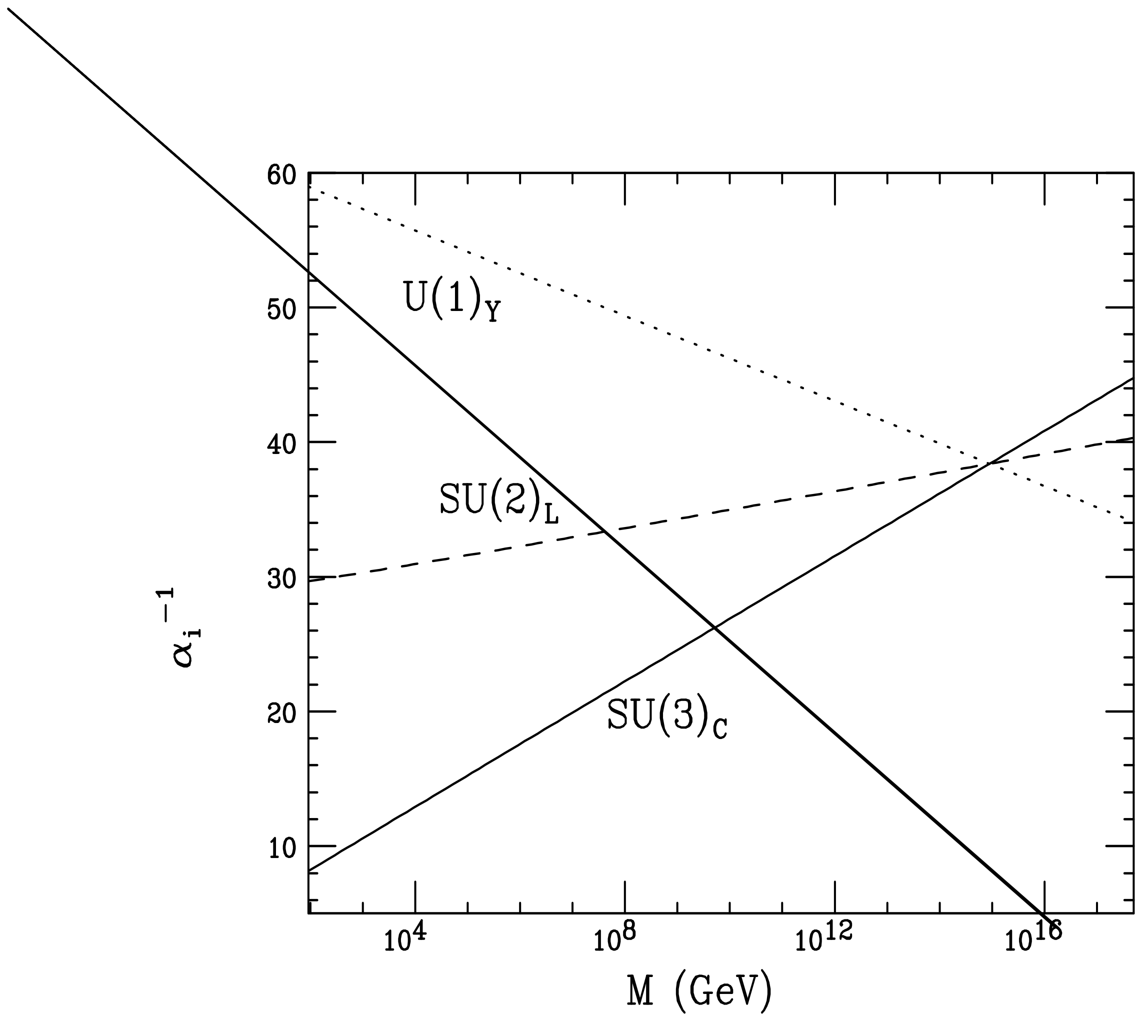


Figure 10: Two-loop RGE evolution of the model with the SM particle content together with a pair of $\tilde{R}_{2L}$ type leptoquarks and an additional Higgs doublet.

As a final comment we note the oft-neglected problem of R-parity violation within a GUT context. A term in the superpotential of the form $\lambda_{ijk}\bar{5}_i\bar{5}_j10_k$ 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[54]. It is not clear, however, that an interaction of the type $e^c d\tilde{u}$ can be generated in this approach with a Yukawa coupling of the right magnitude to explain the HERA events.

9 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 will provide an independent determination of its Yukawa coupling while pair production at the NLC allows one to directly determine all the leptoquark quantum numbers. Lastly, 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 2 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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10 Appendix: Relevant Formulae

Here we collect the relevant formulae 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

$$\frac{d\sigma}{dz} = \frac{\tilde{\lambda}^2 \pi \alpha \alpha_s}{96\hat{s}} \beta \left[v_1 + v_2 + v_3(v_4 + v_5) \right] , \tag{22}$$

with

$$\begin{aligned}
v_1 &= 16 \left(\frac{x_2}{x_1} + \frac{x_4}{m^2} \right) , \\
v_2 &= \frac{8}{(2x_4 + m^2)^2} \left[a(2x_5 x_6 - x_4 m^2) + 2b x_1 x_2 + 2c(x_1 x_6 + x_2 x_5 - x_3 x_4) - 2d x_4 m^2 \right] , \\
v_3 &= \frac{2}{x_1(2x_4 + m^2)} , \\
v_4 &= 32 x_4 x_5 + 16 x_2 x_5 - 16 x_1 x_4 - 32 x_1 x_6 + 16 x_3 x_4 - 16\kappa x_1 x_2 , \\
v_5 &= \frac{2x_1}{m^2} \left[-2x_5 x_6 + (1+\kappa)(x_2 x_5 + x_3 x_4 + x_1 x_6) - x_4 m^2 \right] ,
\end{aligned} \tag{23}$$

and the definitions,

$$\begin{aligned}
a &= -1 + \frac{2\kappa x_3}{m^2} , \qquad b = -2 - 2\kappa + \kappa^2 , \\
c &= 2 + 4\kappa + \frac{(1+\kappa+\kappa^2) x_3}{m^2} , \quad d = 4 - \frac{4x_3}{m^2} - \left[\frac{(1+\kappa)x_3}{m^2} \right]^2 ,
\end{aligned} \tag{24}$$

with

$$\begin{aligned}
x_1 &= \tfrac{1}{2}\hat{s} , & x_2 &= -\tfrac{1}{2}\hat{u} , \\
x_3 &= \tfrac{1}{2}(m^2 - \hat{t}) , & x_4 &= -\tfrac{1}{2}\hat{t} , \\
x_5 &= \tfrac{1}{2}(m^2 - \hat{u}) , & x_6 &= \tfrac{1}{2}(\hat{s} - m^2) , \\
\hat{t} &= -\tfrac{1}{2}(\hat{s} - m^2)(1+z) , & \hat{u} &= -\tfrac{1}{2}(\hat{s} - m^2)(1-z) .
\end{aligned} \tag{25}$$

• SM and Leptoquark Contributions to Drell-Yan Production

The SM contribution to the even and odd kinematic functions are

$$F^{+}_{q(SM)} = 2(1+z^2)\sum_{i,j}(v^i_e v^j_e + a^i_e a^j_e)(v^i_q v^j_q + a^i_q a^j_q)P_{ij}\,, \tag{26}$$

$$F^{-}_{q(SM)} = 4z\sum_{i,j}(v^i_e a^j_e + a^i_e v^j_e)(v^i_q a^j_q + a^i_q v^j_q)P_{ij}\,,$$

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

$$P_{ij} = \frac{\hat{s}^2[(\hat{s}-M_i^2)(\hat{s}-M_j^2)+M_i\Gamma_i M_j\Gamma_j]}{[(\hat{s}-M_i^2)^2+M_i^2\Gamma_i^2][(\hat{s}-M_j^2)^2+M_j^2\Gamma_j^2]}\,, \tag{27}$$

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

$$\begin{aligned} v^\gamma_f &= Q_f\,, & a^\gamma_f &= 0\,, \\ v^Z_f &= \left[\frac{\sqrt{2}G_F M_Z^2}{4\pi\alpha}\right]^{1/2}(T_3 - 2Q_f x_w)\,, & a^Z_f &= \left[\frac{\sqrt{2}G_F M_Z^2}{4\pi\alpha}\right]^{1/2} T_3\,. \end{aligned} \tag{28}$$

The scalar leptoquark contributions to these kinematic functions are

$$\begin{aligned} F^{+}_{q(LQ)} &= -\sum_{i=\gamma,Z}\left[(v^i_e+a^i_e)(v^i_q+a^i_q)\tilde{\lambda}^2_{L,q} + (v^i_e-a^i_e)(v^i_q-a^i_q)\tilde{\lambda}^2_{R,q}\right] P_i \left[\frac{\hat{t}^2}{\hat{s}(\hat{t}-m^2)} + \frac{\hat{u}^2}{\hat{s}(\hat{u}-m^2)}\right] \\ &+\frac{1}{4}\left[\tilde{\lambda}^4_{L,q}+\tilde{\lambda}^4_{R,q}\right]\left[\frac{\hat{t}^2}{(\hat{t}-m^2)^2}+\frac{\hat{u}^2}{(\hat{u}-m^2)^2}\right]\,, \\ F^{-}_{q(LQ)} &= \mp\sum_{i=\gamma,Z}\left[(v^i_e+a^i_e)(v^i_q+a^i_q)\tilde{\lambda}^2_{L,q} + (v^i_e-a^i_e)(v^i_q-a^i_q)\tilde{\lambda}^2_{R,q}\right] P_i \left[\frac{\hat{u}^2}{\hat{s}(\hat{u}-m^2)} - \frac{\hat{t}^2}{\hat{s}(\hat{t}-m^2)}\right] \\ &\pm\frac{1}{4}\left[\tilde{\lambda}^4_{L,q}+\tilde{\lambda}^4_{R,q}\right]\left[\frac{\hat{u}^2}{(\hat{u}-m^2)^2}-\frac{\hat{t}^2}{(\hat{t}-m^2)^2}\right]\,. \end{aligned} \tag{29}$$

Here,

$$P_i = \frac{s(s-M_i)}{(s-M_i^2)^2+M_i^2\Gamma_i^2}\,, \tag{30}$$

and the top sign in the anti-symmetric 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 $e^+e^- \to q\bar{q}$

$$\begin{aligned}
\frac{d\sigma}{dz} &= \frac{3\pi\alpha^2}{2s}\left\{\sum_{ij}\left[(v_e^i v_e^j + a_e^i a_e^j)(v_q^i v_q^j + a_q^i a_q^j)(1+z^2) + 2(v_e^i a_e^j + v_e^j a_e^i)(v_q^i a_q^j + v_q^j a_q^i)z\right]\right. \\
&\quad -\frac{C}{2}\sum_{i=\gamma,Z}\left[(v_e^i + a_e^i)(v_q^i + a_q^i)\tilde{\lambda}_{L,q}^2 + (v_e^i - a_e^i)(v_q^i - a_q^i)\tilde{\lambda}_{R,q}^2\right] P_i \qquad (31) \\
&\qquad \times\left\{\frac{t^2}{s(t-m^2)} + \frac{u^2}{s(u-m^2)} \pm \left[\frac{u^2}{s(u-m^2)} - \frac{t^2}{s(t-m^2)}\right]\right\} \\
&\quad \left. +\frac{C}{8}\left[\tilde{\lambda}_{L,q}^4 + \tilde{\lambda}_{R,q}^4\right]\left\{\frac{t^2}{(t-m^2)^2} + \frac{u^2}{(u-m^2)^2} \pm \left[\frac{u^2}{(u-m^2)^2} - \frac{t^2}{(t-m^2)^2}\right]\right\}\right\}
\end{aligned}$$

with the coupling normalizations and P_{ij}, P_i as defined in Eqs. (27,28,30), and the $\pm$ sign is for

$$\pm \quad \text{for} \quad \left\{\begin{array}{ll} S, & (F=-2) \\ R, & (F=0)\,. \end{array}\right. \qquad (32)$$

References

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

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

[3] S. Pakvasa, Int. J. Mod. Phys. **A2**, 1317 (1987).

[4] For a review, see, K. Lane, lectures given at *Theoretical Advanced Study Institute (TASI93) in Elem. Part. Physics*, Boulder, CO, June 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. **D10**, 275 (1974); G. Senjanovic and A. Sokorac, Z. Phys. **C20**, 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. **D42**, 3892 (1990).

[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] C. Adloff *et al.*, (H1 Collaboration), DESY Report 97-24, hep-ex/970212; J. Breitweg *et al.*, (ZEUS Collaboration), DESY-Report 97-25.

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

[12] V. Barger *et al.*, hep-ph/9703311.

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

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

[15] 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, ed. E.L. Berger (World Scientific, Singapore).

[16] J. Butterworth and H. Dreiner, Nucl. Phys. **B397**, 3 (1993), and in *Second HERA Workshop on Physics*, Hamburg, Germany, Oct. 1991; T. Kon and T. Kobayashi, Phys. Lett. **B270**, 81 (1991); T. Kon, T. Kobayashi, S. Kitamura, K. Nakamura, and S. Adachi, Z. Phys. **C61**, 239 (1994); T. Kon, T. Kobayashi, and S. Kitamura, Phys. Lett. **B333**, 263 (1994), and Int. J. Mod. Phys. **A11**, 1875 (1996).

[17] H. Dreiner and P. Morawitz, hep-ph/9703279; G. Altarelli *et al.*, hep-ph/9703276; D. Choudhury and S. Raychaudhuri, hep-ph/9702392.

[18] W. Buchmüller, R. Rückl, and D. Wyler, Phys. Lett. **B191**, 442 (1987).

[19] S. Davidson, D. Bailey, and B.A. Campbell, Z. Phys. **C61**, 613 (1994).

[20] M. Leurer, Phys. Rev. **D50**, 536 (1994), and **D49**, 333 (1994).

[21] K.S. McFarland *et al.*, FNAL-Pub-97/001-E, hep-ex/9701010.

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

[23] N. Harnew, in *Proceedings of the 1987 HERA Workshop*, Hamburg, Germany, 1987.

[24] See, for example, A.D. Martin, R.G. Roberts, and W.J. Stirling, Phys. Lett. **B387**, 419 (1996); and references therein.

[25] J.A. Grifols and S. Peris, Phys. Lett. **B201**, 287 (1988); J.F. Gunion and E. Ma, Phys. Lett. **195B**, 257 (1987).

[26] J.L. Hewett and S. Pakvasa, Phys. Rev. **D37**, 3165 (1988).

[27] A. Djouadi, J. Ng, and T.G. Rizzo, in *Electroweak Symmetry Breaking and Beyond the Standard Model*, ed. T. Barklow *et al.*, (World Scientific, Singapore), hep-ph/9504210; J. Blümlein, E. Boos, and A. Kryukov, DESY Report 96-174, hep-ph/9610408; B. Dion, L. Marleau, and G. Simon, hep-ph/9610397.

[28] M. de Montigny and L. Marleau, Phys. Rev. **D40**, 2869 (1989), and **D40**, 3616 (1989).

[29] S. Hagopian (D0 Collaboration), presented at *Very Large Hadron Collider Physics and Detector Workshop*, Fermilab, 13-15 March, 1997; K. Maeshima (CDF Collaboration), in *28th International Conference on High Energy Physics*, Warsaw, Poland, July 1996, FNAL-CONF-96/413-E; F. Abe *et al.*, (CDF Collaboration), Fermilab Report FNAL-PUB-96-450-E.

[30] 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*, June 1993, ed. J.L. Hewett, A. White, and D. Zeppenfeld.

[31] J.E. Cieza Montalvo, and O.J.P. Eboli, Phys. Rev. **D50**, 331 (1994).

[32] T.G. Rizzo, Phys. Rev. **D33**, 1851 (1986), and **D34**, 133 (1986).

[33] U. Baur and K.H. Streng, Phys. Lett. **162B**, 387 (1985); R.S. Chivukula, M. Golden and E. Simmons Phys. Lett. **B257**, 403 (1991).

[34] O.J.P. Eboli and A.V. Olinto, Phys. Rev. **D38**, 173 (1988); A. Dobado, M.J. Herrero, and C. Munoz, Phys. Lett. **207B**, 97 (1988); V. Barger *et al.*, Phys. Lett. **B220**, 464 (1989).

[35] R. Ruckl and P. Zerwas, in *Proceedings of the LaThuile Workshop on Physics at Future Accelerators*, LaThuile, Italy, 1987, ed. J.H. Mulvay, CERN Report 87-07 (1987).

[36] F. Abe *et al.*, (CDF Collaboration), Phys. Rev. **D49**, R1 (1994), and Phys. Rev. Lett. **77**, 2616 (1996); S. Abachi *et al.*, (D0 Collaboration), Phys. Rev. Lett. **75**, 1456 (1995).

[37] *Future Electroweak Physics at the Fermilab Tevatron – Report of the Tev-2000 Study Group*, ed. D. Amidei and R. Brock, Fermilab Report FNAL-Pub-96/082 (1996).

[38] M. Peskin and T. Takeuchi, Phys. Rev. Lett. **65**, 964 (1990), and Phys. Rev. **D46**, 381 (1992); W. Marciano and J. Rosner, Phys. Rev. Lett. **65**, 2963 (1990); G. Altarelli and R. Barbieri, Phys. Lett. **B253**, 161 (1990); D. Kennedy and P. Langacker, Phys. Rev. Lett. **65**, 2967 (1990); and Phys. Rev. **D44**, 1591 (1991).

[39] I. Maksymyk, C.P. Burgess, and D. London, Phys. Rev. **D50**, 529 (1994); C.P. Burgess *et al.*, Phys. Lett. **B326**, 276 (1994).

[40] O. Eboli, hep-ph/9508342; O.J. Eboli, M.C. Gonzalez-Garcia, and J.K. Mizukoshi, hep-ph/9612254, and Nucl. Phys. **B443**, 20 (1995); G. Bhattacharyya, J. Ellis, and K. Sridhar, Phys. Lett. **B336**, 100 (1994), and Erratum **B338**, 522 (1994).

[41] J.L. Hewett and T.G. Rizzo, Phys. Rev. **D36**, 3367 (1987); J. Blümlein and R. Rückl, Phys. Lett. **B304**, 337 (1993).

[42] J. Blümlein, E. Boos, and A. Kryukov, Phys. Lett. **B392**, 150 (1997); D. Choudhury, Phys. Lett. **B346**, 291 (1995); J.E. Cieza-Montalvo and O.J. Eboli, Phys. Rev. **D47**, 837 (1993); T.G. Rizzo, Phys. Rev. **D44**, 186 (1991).

[43] H. Dreiner *et al.*, Mod. Phys. Lett. **3A**, 443 (1988); G. Bhattacharyya, D. Choudhury, and K. Sridhar, Phys. Lett. **B349**, 118 (1995); M.S. Berger, hep-ph/9609517.

[44] See, however, LEP/SLD Electroweak Working Group, CERN Report CERN-PPE/96-183 (1996).

[45] J.L. Hewett and S. Pakvasa, Phys. Lett. **B227**, 178 (1989); H. Nadeau and D. London, Phys. Rev. **D47**, 3742 (1993); O.J. Eboli *et al.*, Phys. Lett. **B311**, 147 (1993); G. Belanger, D. London, and H. Nadeau, Phys. Rev. **D49**, 3140 (1994); F. Cuypers, Nucl. Phys. **B474**, 57 (1996); M.A. Doncheski and S. Godfrey, Phys. Rev. **D49**, 6220 (1994), **D51**, 1040 (1995), and hep-ph/9608368.

[46] F. Cuypers, and S. Davidson, PSI-PRD-96-21, hep-ph/9609487.

[47] We would like to thank M. Worah and M. Peskin for pointing out this important observation.

[48] I. Antoniadis, J. Ellis, J.S. Hagelin and D.V. Nanopolous, Phys. Lett. **B194**, 321 (1987).

[49] M. Peskin, private communication.

[50] T.G. Rizzo, Phys. Rev. **D45**, 3903 (1992).

[51] H. Murayama and T. Yanagida, Mod. Phys. Lett. **A7**, 147 (1992).

[52] W.J. Marciano, talk given at the *1983 International Symposium on Lepton and Photon Interactions at High Energies*, Ithaca, NY, August 1983.

[53] R.M. Barnett, *et al.*, (Particle Data Group), Phys. Rev. **D54**, 1 (1996).

[54] See, for example, K. Tamvakis hep-ph/9602389 and hep-ph/9604343 and references therein.