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Don't Stop Thinking About Leptoquarks: Constructing New Models

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Don't Stop Thinking About Leptoquarks: Constructing New Models *

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Abstract

We discuss the general framework for the construction of new models containing a single, fermion number zero scalar leptoquark of mass $\simeq 200 - 220$ GeV which can both satisfy the D0/CDF search constraints as well as low energy data, and can lead to both neutral and charged current-like final states at HERA. The class of models of this kind necessarily contain new vector-like fermions with masses at the TeV scale which mix with those of the Standard Model after symmetry breaking. In this paper we classify all models of this type and examine their phenomenological implications as well as their potential embedding into SUSY and non-SUSY GUT scenarios. The general coupling parameter space allowed by low energy as well as collider data for these models is described and requires no fine-tuning of the parameters.

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1 Introduction and Overview

1.1 *Current Status of the Leptoquark Scenario*

The observation of a possible excess of neutral current(NC) events in e^+p collisions at high$-Q^2$ by both the H1[1] and ZEUS[2] Collaborations have sparked much fervor in both the theoretical and experimental communities. This excitement has now been heightened by the recent announcement that both experiments may also be observing a corresponding excess in the charged-current(CC) channel[3]. If these events are not merely a statistical fluctuation, it is clear that new physics must be invoked in order to provide a suitable explanation, *e.g.*, compositeness appearing in the form of higher dimensional operators[4], exotic modifications of the parton densities[5], or the resonant production of a new particle[7, 8] such as a leptoquark (LQ) or squark in supersymmetric models with R-parity violation.

If the excess is resonant in the x distribution[6], a popular interpretation[7, 8] invoked in the NC case is the $s-$channel production of a $\simeq 200-220$ GeV scalar (*i.e.*, spin-0) leptoquark with fermion number (F) equal to zero. These quantum numbers arise from the requirements that (*i*) the observed excess appears in the e^+p rather than the e^-p channel, (*ii*) the Tevatron search constraints[9] exclude vector (spin-1) leptoquarks with masses near 200 GeV, and (*iii*) any discussion of leptoquark models has been historically based on the classic work by Buchmüller, Rückl and Wyler (BRW)[10]. In that paper the authors provide a set of assumptions under which consistent leptoquark models can be constructed; these we now state in a somewhat stronger form:

(a) LQ couplings must be invariant with respect to the Standard Model (SM) gauge interactions,
(b) LQ interactions must be renormalizable,
(c) LQs couple to only a single generation of SM fermions,
(d) LQ couplings to fermions are chiral,

(e) LQ couplings separately conserve Baryon and Lepton numbers,
(f) LQs only couple to the SM fermions and gauge bosons.

Amongst these assumptions, both (a) and (b) are considered sacrosanct whereas (c)-(e) are data driven[11] by a host of low energy processes. Assumption (f) effectively requires that the leptoquark be the only new component added to the SM particle spectrum which seems quite unlikely in any realistic model. Based on these classical assumptions it is easy to show[10] that all $F = 0$ scalar leptoquarks must have a unit branching fraction into a charged lepton plus jet (*i.e.*, $B_\ell = 1$). This lack of flexibility presents a new problem for the leptoquark interpretation of the HERA events for two reasons: (*i*) leptoquarks with $B_\ell = 1$ clearly cannot accommodate any excess of events in the CC channel at HERA since these would require a sizeable leptoquark decay rate into neutrino plus jet, (*ii*) both CDF[12] and D0[13] have recently presented new limits for the production of scalar leptoquarks at the Tevatron using the next-to-leading order cross section formulae of Krämer *et al.*[14]. In particular, in the $eejj$ channel, D0 finds a 95% CL lower limit on the mass of a $B_\ell = 1$ first generation scalar leptoquark of 225 GeV. D0 has also performed a combined search for first generation leptoquarks by using the $eejj$, $e\nu jj$ and $\nu\nu jj$ channels. For fixed values of the leptoquark mass below 225 GeV, these search constraints can be used to place an upper limit on B_ℓ. For M_{LQ}=200(210,220) GeV, D0 obtains the constraints $B_\ell \leq 0.40(0.62, 0.84)$ at 95% CL. Of course if CDF and D0 combine their searches in the future, then the 225 GeV bound may rise to $\simeq$ 240 GeV, in which case even stronger upper bounds on B_ℓ will be obtained.

Besides the obvious need to provide an potential explanation for the HERA data which satisfies all other experimental constraints, it is perhaps even more important to explore in a more general fashion how one can go beyond the rather restrictive BRW scenarios. Even if the HERA events turn out to be statistical fluctuations, we will show that by the removal of the least tenable of the BRW assumptions, we can find important ways to extend the possible set of leptoquarks that may be realised in nature. Since, as was mentioned above, it is difficult to believe that the addition of the leptoquark would be the only extension to the SM spectrum in any realistic model containing such a field, it is clear that assumption (f) should be abandoned. We now explore the consequences of this possibility.

1.2 *Enlarging the Framework of Leptoquark Models*

In order to satisfy all the experimental constraints it is clear that we need to have an $F = 0$ scalar leptoquark as before, but now with a coupling to SM fermions given by

$$\mathcal{L}_{wanted} = [\lambda_u \nu u^c + \lambda_d e d^c] \cdot LQ + h.c. \,, \tag{1}$$

with comparable values of the Yukawa couplings λ_u and λ_d. This fixes the leptoquark's electric charge to be $Q_{LQ} = \pm 2/3$; no other charge assignment will allow the leptoquark to simultaneously couple to ej and νj as is required by the combination of HERA and Tevatron data. An alternative possibility, if neutrinos are Dirac particles, or if ν^c is light and appears as missing p_T in a HERA or Tevatron detector, is the interaction

$$\mathcal{L}'_{wanted} = [\lambda'_u \nu^c u + \lambda'_d e^c d] \cdot LQ' + h.c. \tag{2}$$

It is important for later analysis to note that these two interactions cannot simultaneously exist as the BRW assumption (d) above would then be strongly violated. Unfortunately, both of these Lagrangians as they stand violate assumption (a) above, in that they are not gauge invariant with respect to $SU(2)_L$. We must then arrive at one of these effective interactions indirectly by some other means than by direct fundamental couplings. In order to do so it is clear that we must be willing to abandon at least one of the BRW assumptions (a)-(f) and it is evident that (f) is the one most easily dismissed. Hence we will assume that the leptoquark has additional interactions besides those associated with SM gauge interactions and the Yukawa couplings to the SM fermions. We note, however, that fine-tuning solutions can be found which allow the assumption (c) to be dropped as a condition that applies in the mass eigenstate basis; these will not be discussed in detail here although it is important to understand how flavor mixing plays a role in leptoquark dynamics in realistic models.

In principle there are several alternatives as to what kinds of new additional interactions one can introduce, two of which we now briefly discuss. In a recent paper, Babu, Kolda and March-Russell[15] considered an interesting model with two different leptoquark doublets, one coupling to Ld^c and the other to Lu^c (with L being the SM lepton doublet). In this model the electric charge $Q = 2/3$ members are mixed through a renormalizable coupling to the SM Higgs field with the mixed leptoquarks forming mass eigenstates that can couple to both ej and νj as desired with the ratio of strengths controlled by the amount of mixing. The new interactions in this case are quite complex and a certain amount of fine tuning is necessary to get the spectrum and couplings to come out as desired. The rich phenomenology of this scenario, which now involves four leptoquark mass eigenstates of various charges, should be further studied in detail. A second scenario has only been briefly mentioned in the recent paper by Altarelli, Giudice and Mangano[16] who considered the possibility of at least temporarily violating both conditions (a) and (b) via non-renormalizable operators. These authors show, however, that both (a) and (b) can be restored by the introduction of new heavy fermions to which the leptoquarks couple in a gauge invariant fashion and which are then integrated out to obtain the desired effective low energy Lagrangian above. In this case there is only one isosinglet $Q = 2/3$ leptoquark present, which turns out to be quite advantageous.

In this paper we will consider and classify all models wherein heavy fermions are used to generate the effective interactions $\mathcal{L}_{wanted}$ or $\mathcal{L}'_{wanted}$ at low energies. As we will see, the emphasis of our approach is somewhat different than that of Altarelli *et al.*, in that we will keep the new heavy fermions as active ingredients in our models and not treat them as an auxiliary device to produce the desired coupling structure. In particular, we will assume that exotic, vector-like fermions exist and that the desired interactions are induced through their couplings to the leptoquark and their mixing with the SM fermions. The mixing between the new fermions and those of the SM will be generated by conventional spontaneous symmetry breaking (SSB) via the usual Higgs doublet mechanism. It is only through SSB that the above effective Lagrangian can be obtained in the fermion mass eigenstate basis from an originally gauge invariant interaction. The small size of the effective Yukawa couplings in the above Lagrangians, $\mathcal{L}_{wanted}$ or $\mathcal{L}'_{wanted}$, are then directly explained by the same mechanism that produces the ordinary-exotic fermion mixing and automatically sets the scale of the vector-like fermion masses in the TeV region. We note that the use of vector-like fermions in this role is particularly suitable since in their unmixed state they make essentially no contribution to the oblique parameters[18], they are automatically anomaly free, and they can have bare mass terms which are SM gauge invariant. (Alternatively, their masses can be generated by the vacuum expectation value of a SM singlet Higgs field.) Mixing with the SM fermions does not significantly detract from these advantages as we will see below. As is by now well-known[8], the leptoquark itself does not significantly contribute to the oblique parameters provided it is either an isosinglet, which will be the case realised in all of the models below, or in a degenerate multiplet.

Before discussing the construction of new leptoquark models with vector-like fermions, it is interesting to note that HERA will not be able to distinguish between the two scenarios described above, even if the relative ej and νj branching fractions are precisely measured. The only means of differentiating the models is to either find the other new particles anticipated in each scheme, or to directly produce the $\simeq 200-220$ GeV leptoquarks at a high energy e^+e^- collider such as the NLC[8]. As we will see below, the charge and weak isospin of the leptoquark is fixed in the models with vector-like fermions and is independent of the

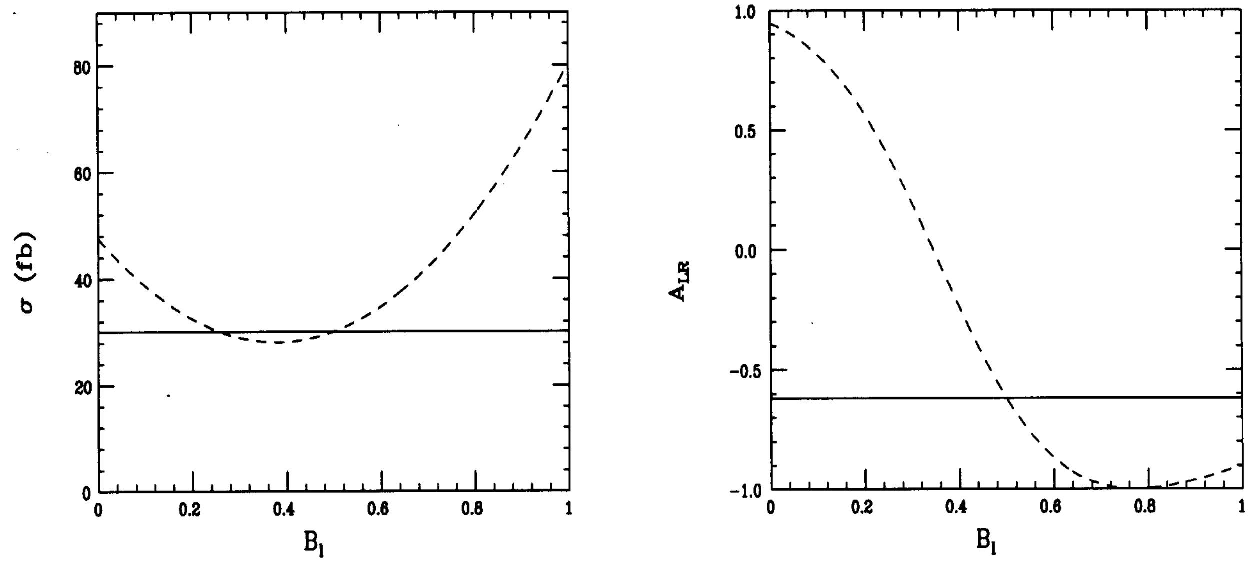


Figure 1: Cross section(left) and associated polarization asymmetry(right) for the production of a pair of 200 GeV leptoquarks at a 500 GeV NLC. The dashed curve is the model of Babu, Kolda and March-Russell while the solid line is the prediction of the model with vector-like fermions.

value of B_ℓ. However, in the Babu *et al.* approach the leptoquark's effective weak isospin is highly correlated with the value of B_ℓ. Fig.1 displays a comparison of the leptoquark pair production cross section and polarization asymmetry for these two models at a 500 GeV NLC. It is clear that unless B_ℓ is very close to 50% the two scenarios will be easily separated at the NLC. These results also show that a leptoquark with the quantum numbers anticipated in vector-like fermion models is trivially distinguishable from the more conventional BRW leptoquarks by the same analysis[8].

1.3 *Constraints on Leptoquark Coupling Parameters*

As we will find below, in models with vector-like fermions, the only new physics at low energies introduced by the leptoquark itself can be parameterized in terms of the interactions in $\mathcal{L}_{wanted}$. It is then straightforward to use existing data to constrain the effective Yukawa couplings $\lambda_{u,d}$; here, we can express λ_u in terms of $B_\ell = \lambda_d^2/(\lambda_d^2+\lambda_u^2)$, since we assume that the leptoquark has no other decay modes. As discussed above, the Tevatron searches place a λ_d independent constraint on B_ℓ for any fixed value of the leptoquark mass. Similarly, the recent measurements of Atomic Parity Violation (APV) in Cesium[19] place B_ℓ independent bounds on λ_d[20] for fixed values of M_{LQ}. In addition, universality in π decay constrains the product $\lambda_u\lambda_d$[21], while the observed rate of NC events at HERA constrains instead the product $\lambda_d^2 B_\ell$; in the later case QCD corrections are quite important[22]. The latest available results presented by both the ZEUS and H1 Collaborations[23] in the neutral current as well as the charged current are included in our estimate of the cross section constraints for both channels. (We note that due to the relatively low statistics and other uncertainties the errors in this case are probably significantly underestimated so that this band is actually somewhat wider than what is shown below.) Combining these constraints defines an approximate allowed region in the $B_\ell - \tilde\lambda_d$ plane which is presented in Fig.2 for $M_{LQ} = 200, 210, 220$ GeV. Here, $\tilde\lambda = \lambda/e$ with e being the conventional proton charge (this scaling of the coupling to e follows earlier tradition[24]). We note that the size of the (apart from the HERA data) 95% CL allowed region is sensitive to the two possible choices of the sign of the product of $\tilde\lambda_u\tilde\lambda_d$. As we will see below, the region corresponding to $\tilde\lambda_u\tilde\lambda_d > 0$ is preferred so that the π decay data has little impact in restricting the parameter space. From Fig.2 we see that the position of the allowed region moves up and to the right as the mass of the leptoquark increases from 200 to 220 GeV. For the case $\tilde\lambda_u\tilde\lambda_d > 0$, the size of the allowed region is not greatly affected as the leptoquark mass increases whereas, for $\tilde\lambda_u\tilde\lambda_d < 0$ the region grows significantly in area with increasing mass. The size of the allowed region in each case would be substantially smaller if CDF and D0 could combine their results and further constrain the value of B_ℓ.

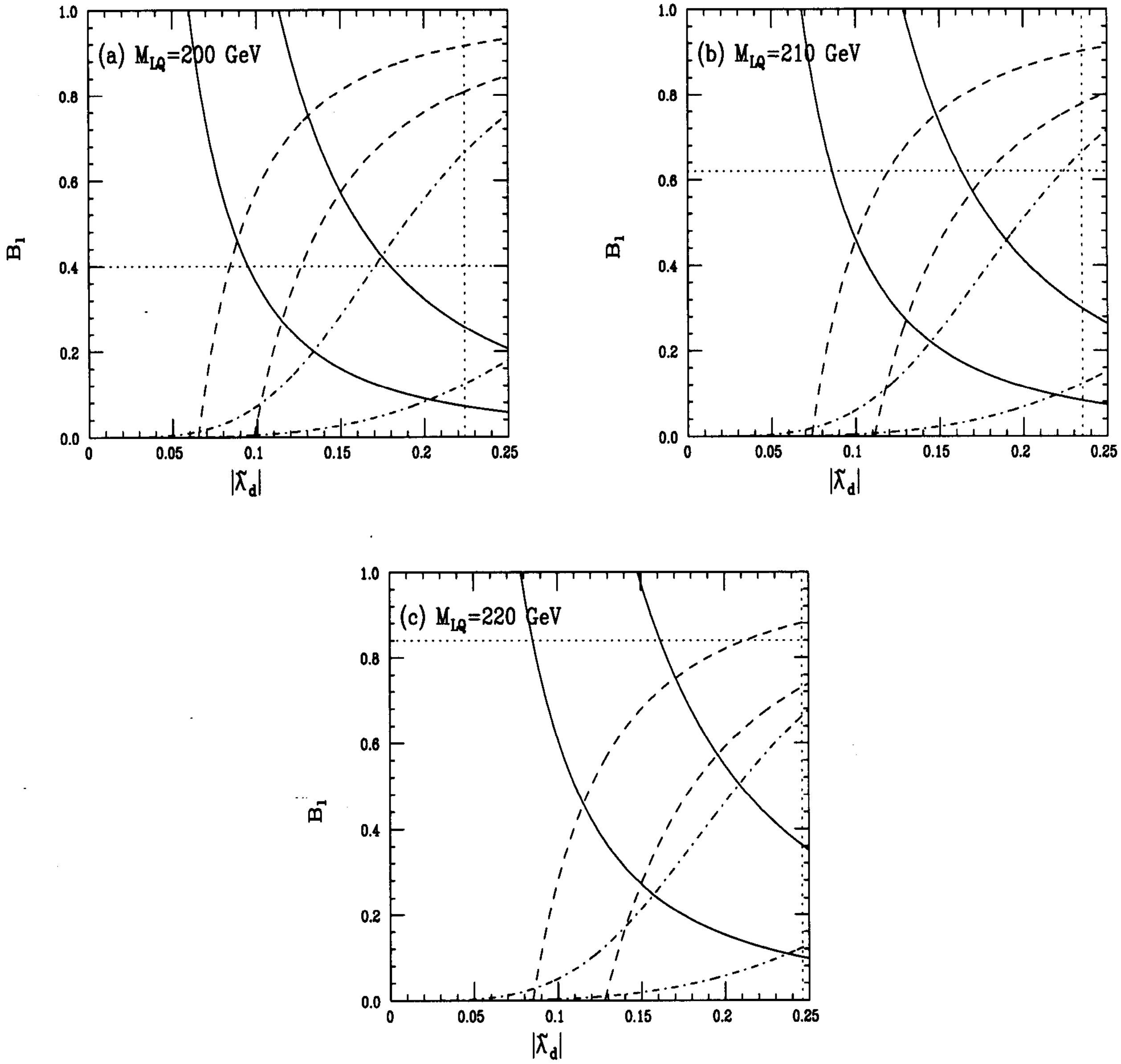


Figure 2: Allowed parameter space region in the $B_\ell - \tilde{\lambda}_d$ plane for a leptoquark with mass 200 GeV(top left), 210 GeV(top right) or 220 GeV(bottom). The region allowed by Tevatron searches is below the horizontal dotted line while that allowed by APV data is to the left of the vertical dotted line. The region inside the solid band is required to explain the HERA excess in the NC channel at 1σ. The region between the dashed curves corresponds to the 1σ range required to explain the apparent excess at HERA in the charge current channel. The region above the dash-dotted curve is allowed by π decay universality: the lower(upper) curve corresponds to the case where $\tilde{\lambda}_u\tilde{\lambda}_d > (<)0$.

In addition to the constraints shown in Fig.2, further leptoquark coupling information can potentially be obtained[16] from examining the sum of the squares of the first row of the Cabbibo-Kobayashi-Maskawa (CKM) weak mixing matrix, $\sum_i |V_{ui}|^2$. In the SM this sum is, of course, unity, but leptoquark exchange in β decay can yield either an upward or downward shift in the extracted value of $|V_{ud}|$ of

$$|V_{ud}|^2_{eff} \simeq |V_{ud}|^2_{true} - 1.52 \times 10^{-3} \left(\frac{200\ GeV}{M_{LQ}}\right)^2 \left(\frac{\tilde{\lambda}_u}{0.15}\right) \left(\frac{\tilde{\lambda}_d}{0.15}\right), \tag{3}$$

so that it would appear experimentally as if a unitarity violation were occurring. Interestingly, the value of the above sum has recently been discussed by Buras[25], who reports $\sum_i |V_{ui}|^2 = 0.9972 \pm 0.0013$, which is more than 2σ below the SM expectation. Clearly, if $\tilde{\lambda}_u\tilde{\lambda}_d > 0$, leptoquark exchange provides one possible additional contribution which, for $\tilde{\lambda}_u = \tilde{\lambda}_d = 0.15$ (implying $B_\ell = 1/2$) and $M_{LQ} = 200$ GeV, would increase the sum to the value 0.9987. If we take this new determination of V_{ud} seriously, then the constraint on leptoquark parameters from CKM unitarity can be written in terms of $\tilde{\lambda}_d$ and B_ℓ at the 1σ level as (for the case of same sign leptoquark couplings)

$$2.8 \pm 1.3 = 1.52 \left(\frac{200\ GeV}{M_{LQ}}\right)^2 \left(\frac{\tilde{\lambda}_d}{0.15}\right)^2 \sqrt{\frac{1-B_\ell}{B_\ell}}, \tag{4}$$

which is easily satisfied over most of the allowed parameter space in Fig.2. As we will see below, the mixing between the SM and vector-like fermions can also yield an additional small positive or negative contribution to $|V_{ud}|^2_{eff}$ which can have an effect on the CKM unitarity condition in some models.

2 Analysis and Construction of New Leptoquark Models

Employing the BRW assumptions (a)-(e) listed above we can construct our new extended set of leptoquark models using the following prescription:

(*i*) The leptoquark couples a SM fermion multiplet, one of $(L, Q, u^c, d^c, e^c, (\nu^c))$, where Q is the usual left-handed quark doublet, to an exotic vector-like fermion X_i (or X_i^c) in a gauge invariant manner. For simplicity, the vector-like fermion is assumed to be an isosinglet or isodoublet under $SU(2)_L$ and either a singlet, triplet, or anti-triplet with respect to $SU(3)_C$. $X_i(X_i^c)$ will denote the new fields with fermion number $F > (<)0$.

(*ii*) If $X_i(X_i^c)$ couples a SM fermion with a given helicity to the leptoquark, then $X_i^c(X_i)$ couples via H or H^c to the SM fermion of the opposite helicity, where H/H^c are conventional doublet Higgs fields. We introduce both H/H^c fields as independent degrees of freedom to allow for supersymmetrization of the models we construct.

(*iii*) To obtain the effective Lagrangian in Eqn. (1) we require that terms of the form $\mathcal{N}\mathcal{U}^c + h.c.$ and $\mathcal{E}\mathcal{D}^c + h.c.$ must *both* appear in the original Lagrangian before spontaneous symmetry breaking by the H/H^c vacuum expectation values (vevs), where one of $\mathcal{N}(\mathcal{U}^c)$ and $\mathcal{E}(\mathcal{D}^c)$ must be a SM fermion field. This insures that a $Q = -1(0)$ lepton will couple to a $Q = -1/3(+2/3)$ quark to produce an $F = 0$ leptoquark and that the type of structure in $\mathcal{L}_{wanted}$ can be obtained after mixing.

(*iv*) Bare mass terms for the fields X_i of the form $M_i X_i X_i^c$ must be added to the original Lagrangian.

(*v*) We follow the BRW assumptions (a)-(e) catalogued in the introduction.

We note that in the supersymmetric version of these models, the conjugate leptoquark field LQ^c must also be present and that it cannot couple directly to any of the SM fermion fields, due to gauge invariance, unless it mixes with the leptoquark. This implies, in the zero $LQ - LQ^c$ mixing limit, that the conjugate leptoquark field cannot be produced at HERA, and that its production signature at the Tevatron will necessarily be quite different than that of the leptoquark and will have thus escaped detection, even though the LQ^c pair production cross section is the same as that for leptoquark pairs of the same mass. We will briefly discuss the more complex situation which includes this type of mixing below.

We now begin to classify all possible models which employ SM and vector-like fermion mixing to obtain the desired leptoquark couplings. We will take one SM fermion multiplet at a time and pair it with a vector-like fermion and a leptoquark. Since there are six SM fermion multiplets (allowing for the possibility of ν^c) there are naively at most six possible models that can be constructed. (As we will see the actual number is somewhat more than this since various combinations of these models are feasible.) To demonstrate how these construction rules work in practise, we begin by considering the first case in detail. Here, we couple an exotic fermion, denoted as X_1, to L plus a leptoquark, *i.e.*, $LX_1^c \cdot LQ$. In this case (*iii*) above requires that X_1 be an isodoublet, with member charges of $2/3, -1/3$ since the leptoquark charge is fixed, as well as an $SU(3)_C$ triplet. The BRW assumption (a) then dictates that the leptoquark be an isosinglet. We can thus write $X_1^T = (U^0, D^0)$, where the superscript denotes the weak eigenstate fields. (*ii*) and (*iv*) above then instruct us to add the SM gauge invariant terms $X_1 u^c H + X_1 d^c H^c$ and $M_1 X_1 X_1^c$ to the Lagrangian. Including the Yukawa couplings (which we assume are of order unity) these terms, together with the gauge interactions of both the leptoquark and the fermion doublet X_i, form our new set of interactions that are added to the SM. Denoting this as model A, we thus arrive at

$$\mathcal{L}_A = \lambda_A L X_1^c \cdot LQ + a_u X_1 u^c H + a_d X_1 d^c H^c - M_1 X_1 X_1^c + gauge + h.c.\,, \qquad (5)$$

where '*gauge*' represents the new gauge interactions of the leptoquark and X_1. We emphasize that all of the above Yukawa couplings are assumed to be of order unity.

When H and H^c receive vevs (v and v^c), the $a_{u,d}$ terms in the above Lagrangian induce off-diagonal couplings in both the $Q = -1/3$ and $Q = 2/3$ quark mass matrices. Neglecting the u- and d-quark masses, these are given in the $\bar{\psi}_L^0 M \psi_R^0$ weak eigenstate basis by

$$\bar{\psi}_L^0 M_u \psi_R^0 = (\bar{u}^0, \bar{U}^0)_L \begin{pmatrix} 0 & 0 \\ a_u v & -M_1 \end{pmatrix} \begin{pmatrix} u^0 \\ U^0 \end{pmatrix}_R , \tag{6}$$

$$\bar{\psi}_L^0 M_d \psi_R^0 = (\bar{d}^0, \bar{D}^0)_L \begin{pmatrix} 0 & 0 \\ a_d v^c & -M_1 \end{pmatrix} \begin{pmatrix} d^0 \\ D^0 \end{pmatrix}_R . \tag{7}$$

Both $M_{u,d}$ can be diagonalized by a bi-unitary transformation which becomes bi-orthogonal under the assumption that the elements of $M_{u,d}$ are real, resulting in the diagonal mass matrices $M_{u,d}^{diag} = U_L(u,d) M_{u,d} U_R(u,d)^\dagger$. Since $U_{L,R}(u,d)$ are simple 2×2 rotations they can each be parameterized by a single angle $\theta_{L,R}^{u,d}$. For the case at hand $\theta_L^{u,d} = 0$, whereas $\theta_R^{u,d} \simeq a_{u,d} v(v^c)/M_1$. Taking the Yukawa couplings to be of order unity and $v, v^c \sim 100-250$ GeV, the size of the mixing is fixed by the scale of M_1. Writing $U^0 \simeq U + \theta_R^u u$ in terms of the mass eigenstate fields, and similarly for D^0, the interaction involving the SM fermions and the leptoquark thus becomes

$$\mathcal{L}_{light} = \left[\left(\frac{\lambda_A a_u v}{M_1} \right) \nu u^c + \left(\frac{\lambda_A a_d v^c}{M_1} \right) e d^c \right] \cdot LQ + h.c. , \tag{8}$$

which is the exact form we desired in Eqn. (1). This naturally leads to a reasonable relative branching fraction for the $LQ \to \nu j$ decay mode, and gives acceptable values for $\lambda_{u,d}$ in Eqn. (1) for M_1 in the 1-5 TeV range.

At this point one may note that we have omitted a term in $\mathcal{L}_A$ of the form $-M'QX_1^c$, with M' being a bare mass parameter. Such a term is, of course, gauge invariant and should be present in principle but has little influence on the scenario as far as the leptoquark interactions are concerned. Of course one can always invent a symmetry to forbid this term if so desired as in practice such a term may produce an uncomfortably large mass for the SM fermions, induced by mixing, and so additional care is required. However, to keep the following discussion as general as possible, such terms will be included in our discussion. With M' being the same order as M_1 there is essentially no change in our result for the right-handed mixing above; we now obtain $\theta_R^{u,d} \simeq a_{u,d}v(v^c)M_1/(M_1^2 + M'^2) \simeq a_{u,d}v(v^c)/M_1$. However, M' induces a non-zero mixing for the left-handed fields, but this does not influence either the leptoquark or Z boson couplings to the light fermions. There is a new contribution in the case of the light fermions' charged current couplings to the W, but it is quite suppressed being proportional to $\Delta = 1 - \cos(\theta_L^u - \theta_L^d)$, with the difference $\theta_L^u - \theta_L^d \simeq (a_u^2 v^2 - a_d^2 v^{c2})/M_1^2$ being small. Note that while both $\theta_L^{u,d}$ are large, neither is directly observable and it is the *difference* between the two, which is very small, that is observable. It is also important to remember that this mixing angle difference is also proportional to $B_\ell^2 - (1 - B_\ell)^2$, so that it is further suppressed for values of B_ℓ approaching 0.5. Even without considering these cancellations, we estimate the effect to be very small since the difference in the left-handed mixing angles is roughly given by $\theta_L^u - \theta_L^d \sim \theta_R^2 \simeq (0.05)^2$, implying $\Delta < 10^{-5}$. In the next section we will return to the general question of whether the effects associated with the finite size of these mixing angles can lead to observable shifts in SM expectations.

To proceed with our systematic analysis, we first list the remaining five skeleton models that are obtained by simply combining the other SM representations with an appropriate vector-like fermion and leptoquark field (note that both models B and F involve the field

ν^c):

$$\begin{aligned}
\mathcal{L}_B &= \lambda_B Q X_2^c \cdot LQ + a_e X_2 e^c H^c + a_\nu X_2 \nu^c H - M_2 X_2 X_2^c\,, \\
\mathcal{L}_C &= \lambda_C X_3 u^c \cdot LQ + a_1 L X_3^c H - M_3 X_3 X_3^c\,, \\
\mathcal{L}_D &= \lambda_D X_4 d^c \cdot LQ + a_2 L X_4^c H^c - M_4 X_4 X_4^c\,, \qquad (9) \\
\mathcal{L}_E &= \lambda_E X_5 e^c \cdot LQ + a_3 Q X_5^c H^c - M_5 X_5 X_5^c\,, \\
\mathcal{L}_F &= \lambda_F X_6 \nu^c \cdot LQ + a_4 Q X_6^c H - M_6 X_6 X_6^c\,,
\end{aligned}$$

where the usual '*gauge + h.c.*' terms have been dropped for simplicity. Note that model B is essentially the leptonic equivalent of model A; here, the vector-like fermion field X_2 is a color singlet, weak isodoublet, *i.e.*, $X_2^T = (N^0, E^0)$, and the leptoquark remains an isosinglet. This model requires the neutrino to be a light Dirac field or, at the very least, ν^c to appear as missing p_T in the leptoquark decay process.

It is important to notice that some of these individual skeleton models *do not* satisfy all of the model building constraints listed above, in particular (*iii*). However, this requirement can be satisfied by taking combinations of the various skeleton $\mathcal{L}_i$ above, taking care not to violate the BRW condition (d) that the leptoquark couplings remain chiral. The weaknesses in models C and D as well as E and F can be overcome by simply pairing them:

$$\begin{aligned}
\mathcal{L}_{CD} &= [\lambda_C N u^c + \lambda_D E d^c] \cdot LQ + a_1 L N^c H + a_2 L E^c H^c - M_N N N^c - M_E E E^c\,, \\
\mathcal{L}_{EF} &= [\lambda_E D e^c + \lambda_F U \nu^c] \cdot LQ + a_3 Q D^c H^c + a_4 Q U^c H - M_D D D^c - M_U U U^c\,, \qquad (10)
\end{aligned}$$

where the superscript '0' denoting the weak eigenstate has been dropped for simplicity. Both models CD and EF now satisfy all of our model building requirements, however, it is important to realize that these two combinations are *not* the only set of alternatives. In this case, the fields U, D, N and E are identified with $X_{6,5,3,4}$, respectively, and are all weak isosinglets with the field notation designating the color and charge information. Note that the individual bare mass terms are present for these fields, and that in both models the leptoquark is again an isosinglet with charge 2/3. As in the case of model B, model EF requires ν^c to appear as missing p_T in the leptoquark decay, otherwise these models are excluded by the apparent HERA CC excess and, possibly, by the Tevatron constraints. We note that, as in the case of model A, additional gauge invariant mass/mixing terms can be added to the Lagrangians of models B, CD and EF. These take the form of $-M'_L L X_2^c$ for model B, $-M'_N N\nu^c - M'_E E e^c$ for model CD and $-M'_D D d^c - M'_U U u^c$ for model EF. They produce essentially no additional new physics effects at a visible level in the latter two cases since none of the SM fermion couplings to the gauge bosons are further altered. However, in model B, as was seen for model A, a modification of the SM leptonic CC couplings to the W boson will occur and is proportional to the square of the difference in the left-handed mixing angles needed to diagonalize the neutral and charged lepton mass matrices. For completeness, the mass matrices for the vector-like and SM fermion sector for each of these models are as follows (using the same weak eigenstate basis as above): for model B,

$$M_\nu = \begin{pmatrix} 0 & -M'_L \\ a_\nu v & -M_2 \end{pmatrix}, \tag{11}$$

$$M_e = \begin{pmatrix} 0 & -M'_L \\ a_e v^c & -M_2 \end{pmatrix}, \tag{12}$$

whereas for model CD we find

$$M_\nu = \begin{pmatrix} 0 & a_1 v \\ -M'_N & -M_N \end{pmatrix}, \tag{13}$$

$$M_e = \begin{pmatrix} 0 & a_2 v^c \\ -M'_E & -M_E \end{pmatrix}, \tag{14}$$

and for model EF we correspondingly obtain

$$M_u = \begin{pmatrix} 0 & a_4 v \\ -M'_U & -M_U \end{pmatrix}, \tag{15}$$

$$M_d = \begin{pmatrix} 0 & a_3 v^c \\ -M'_D & -M_D \end{pmatrix}, \tag{16}$$

where in all cases we have allowed for the additional gauge invariant terms discussed above. With the primed and unprimed bare mass terms of roughly the same magnitude, the effective $\lambda_{u,d}$ (or $\lambda'_{u,d}$) couplings can be read off directly from these matrices and the above Lagrangians are expressible in the same form as in Eq. 8 with the appropriate substitutions of masses and Yukawa couplings. It is important to remember that in models CD and EF, which involve mixings with isosinglet fermions, the roles of the left- and right-handed mixing angles, θ_L and θ_R, are essentially interchanged with respect to those in models A and B where the vector-like fermions are in isodoublets. In all cases the relevant mixing angles are of order 0.05 as obtained in the case of model A, due to the phenomenological constraints imposed on the effective Yukawa couplings by the HERA data.

Lastly, we note that models A, B, CD and EF are not the only successful ones that can be constructed. We can, *e.g.*, take either model A or B and combine it with one of the skeleton models C-F; for example, model B could be coalesced with F. In principle, many potential hybrid models of this type can be constructed. This observation will be important below when we discuss the unification of these models within a GUT framework, as well as the phenomenological implications of the SM and vector-like fermion mixing. We note that in these more complex models the fermion mixing(s) that generate the SM fermion couplings to the leptoquark can arise from multiple sources. Of course, when we attempt to construct further hybrid models, we must take care not to violate the assumption that the leptoquark couplings are chiral. Given this very strong constraint, the entire list of models that can be constructed in this fashion are only ten in number: A, B, CD, EF; AC, AD, ACD, BE, BF and BEF. We note that models A, CD, AC, AD and ACD produce the effective interaction $\mathcal{L}_{wanted}$, while models B, EF, BE, BF and BEF produce instead $\mathcal{L}'_{wanted}$. The models and the exotic fermions associated with each of them are catalogued in Table 3.

3 Implications and Tests

Some phenomenological implications of these models are examined in this section. The detailed phenomenology depends on whether or not supersymmetry (SUSY) is also introduced. Clearly, the non-SUSY versions are more easily analyzed but both classes of models share many common features which we will discuss here. These include new interactions due to the mixing between the vector-like and SM fermions as well as from the existence of the leptoquark and the vector-like fermions themselves.

3.1 *Direct Production of Vector-Like Fermions*

The production and decay of vector-like fermions has been extensively discussed in the literature[24, 26], particularly in the context of E_6 grand unified theories. The mixing induced between these new fields and the ordinary SM fermions not only modifies the SM fermion couplings to the W and Z but also leads to flavor-changing Z interactions involving a single SM fermion and a vector-like fermion. This implies that the vector-like fermions can be produced in pairs via the usual mechanisms, or singly via mixing. Once produced, they can decay through mixing into a SM fermion and a Z or W with comparable rates. However, unlike most models containing vector-like fermions, it is more likely here that at least some of these states will dominantly decay to leptoquarks instead due to the large

Model	Vector-like Fermions
A	$\begin{pmatrix} U \\ D \end{pmatrix}_{L,R}$
CD	$N_{L,R}; E_{L,R}$
AC	$\begin{pmatrix} U \\ D \end{pmatrix}_{L,R} ; N_{L,R}$
AD	$\begin{pmatrix} U \\ D \end{pmatrix}_{L,R} ; E_{L,R}$
ACD	$\begin{pmatrix} U \\ D \end{pmatrix}_{L,R} ; N_{L,R}; E_{L,R}$
B	$\begin{pmatrix} N \\ E \end{pmatrix}_{L,R}$
EF	$U_{L,R}; D_{L,R}$
BE	$\begin{pmatrix} N \\ E \end{pmatrix}_{L,R} ; D_{L,R}$
BF	$\begin{pmatrix} N \\ E \end{pmatrix}_{L,R} ; U_{L,R}$
BEF	$\begin{pmatrix} N \\ E \end{pmatrix}_{L,R} ; U_{L,R}; D_{L,R}$

Table 1: Listing of models and the vector-like fermions which are contained in them.

assumed size of the Yukawa couplings. Given the expected large mass of the new fermions in these models, they will only be accessible at the LHC (until $\sqrt{s}$=2-10 TeV e^+e^- or $\mu^+\mu^-$ colliders are constructed). For masses of order 1 TeV and an integrated luminosity of 100 fb^{-1}, we estimate the yield of color triplet vector-like fermion pairs at the LHC to be of order 10^4 events, where they are produced by a combination of gg and $q\bar{q}$ fusion. If the W and Z final states produced in the vector-like fermion decays can be triggered on with reasonable efficiency this implies that the production of such heavy states should be relatively straightforward[27]. The production and detection of heavy color-singlet states at a reasonable rate seems somewhat more problematic[26] due to background issues.

3.2 *Universality Violations Revisited*

Do the vector-like fermions have visible indirect effects at lower energies? We first examine whether the vector-like and SM fermion mixing itself induces a sizeable universality violation. Here, the cases where the vector-like fermions are isodoublets or isosinglets induce quite different effects; recall that in the isodoublet vector-like fermion scenario, $\theta_R \sim 0.05$ and the difference $\theta^u_L - \theta^d_L \sim (0.05)^2$, whereas the reverse is true in the case of isosinglet fermions. We thus find the following shifts in the CKM element $|V_{ud}|^2$ in each of the above principle models (to leading order in the mixing angles)

$$\begin{aligned} A &: -(\theta^u_L - \theta^d_L)^2 + (\theta^u_R \theta^d_R)^2 \,, \\ B &: 0 \,, \\ CD &: 0 \,, \\ EF &: -(\theta^u_L)^2 - (\theta^d_L)^2 \,. \end{aligned} \tag{17}$$

Clearly the effect is very small in the models with isodoublet quarks (model A), but can be sizable in the isosinglet quark case (model EF). In fact, for model EF we see that the effect of mixing is to decrease the value of $|V_{ud}|^2_{eff}$ relative to the SM expectation by an amount of order 10^{-3}; this is at the level of current sensitivity, as discussed in the previous section, and is comparable to the size of the present difference between experiment and the expectations of unitarity.

The other consequence to notice above is the null result in the case of models B and CD. In these scenarios, the same mixing that affects nuclear decays also appears in the calculation of μ decay and is therefore absorbed into the definition of G_F. However, a residual effect from the mixing will remain in the ratio of widths for $\pi \to e\nu$ to $\pi \to \mu\nu$. This results in another shift in these models, in addition to that from the leptoquark exchange discussed above, from the SM expectation for this ratio by an amount

$$\begin{aligned} B &: -(\theta^\nu_L - \theta^e_L)^2 - (\theta^\nu_R \theta^e_R)^2 , \\ CD &: -(\theta^\nu_L)^2 - (\theta^e_L)^2 , \end{aligned} \tag{18}$$

which is negative and can be sizeable in the case of model CD for mixing angles of order 0.05. Experimentally[21], the value of this universality testing ratio to its SM expectation is found to be 0.9966 ± 0.0030; we note that the potential deviation from unity is comparable to the expectation in model CD.

Lastly, we note that in model B a right-handed charged current is generated for the electron, which could in principle be observed in μ decay if ν^c appeared as missing energy or p_T. However, the size of the right-handed amplitude generated through this mixing is far too small (by several orders of magnitude) to be detected in the Michel spectrum[21].

3.3 $g-2$ *of the Electron and Electron Neutrino*

One reason for demanding that the leptoquark couplings to fermions be chiral is to avoid the enhancement of a number of loop-order processes, *e.g.*, the $g-2$ of the electron. Here we have successfully constructed chirally coupled leptoquark models and hence their contribution to the electron's $g-2$ is very small, however, there remains the possibility that the mixings between the SM and vector-like fermions may reinstate significant contributions to a_e. Model B provides an example of this scenario, since in this case, both left- and right-handed leptonic couplings to the W-boson exist and the heavy N can participate in a_e as an intermediate state. The contribution in this case can be immediately obtained from Ref.[28] and directly compared with the prediction of the SM[29] and the experimental value. For the difference between the latter two we find (with the total uncertainty in the difference given in parenthesis)

$$a_e^{exp} - a_e^{SM} = -13.2(27.2) \times 10^{-12}\,, \tag{19}$$

while the additional contribution in the case of model B can be written as

$$\Delta a_e = (-34346 \times 10^{-12}) F(x) \sin(\theta_L^\nu - \theta_L^e) \sin\theta_R^e\,, \tag{20}$$

where $F(x)$ is a kinematical function of the mass ratio $x = M_N^2/M_W^2$. The large numerical size of the prefactor gives some warning that the effect might be of a reasonable magnitude even though it is highly suppressed by several powers of mixing angle factors. Taking $\theta_R \sim 0.05$ and the difference $\theta_L^\nu - \theta_L^e \sim (0.05)^2$ as usual, we obtain the results displayed in Fig.3; note that the absolute value of the shift is presented since the signs of the mixing angles are unknown. This analysis demonstrates that for typical ranges of the parameters in this model, the size of Δa_e is comparable to or larger than the present uncertainty in the value of a_e; hence values of $M_N \gtrsim 5$ TeV are excluded for these suggestive sizes of the mixing angles.

In a similar fashion the corresponding contribution to the magnetic moment of the electron neutrino, κ_ν, can be obtained, provided that ν_e is a Dirac fermion. (We recall that both the electric and magnetic dipole moments of a Majorana neutrino vanish identically.) In this case the amplitude arises from a penguin diagram with the vector-like fermion E in the intermediate state. The results thus take similar form to that for Δa_e above, except that

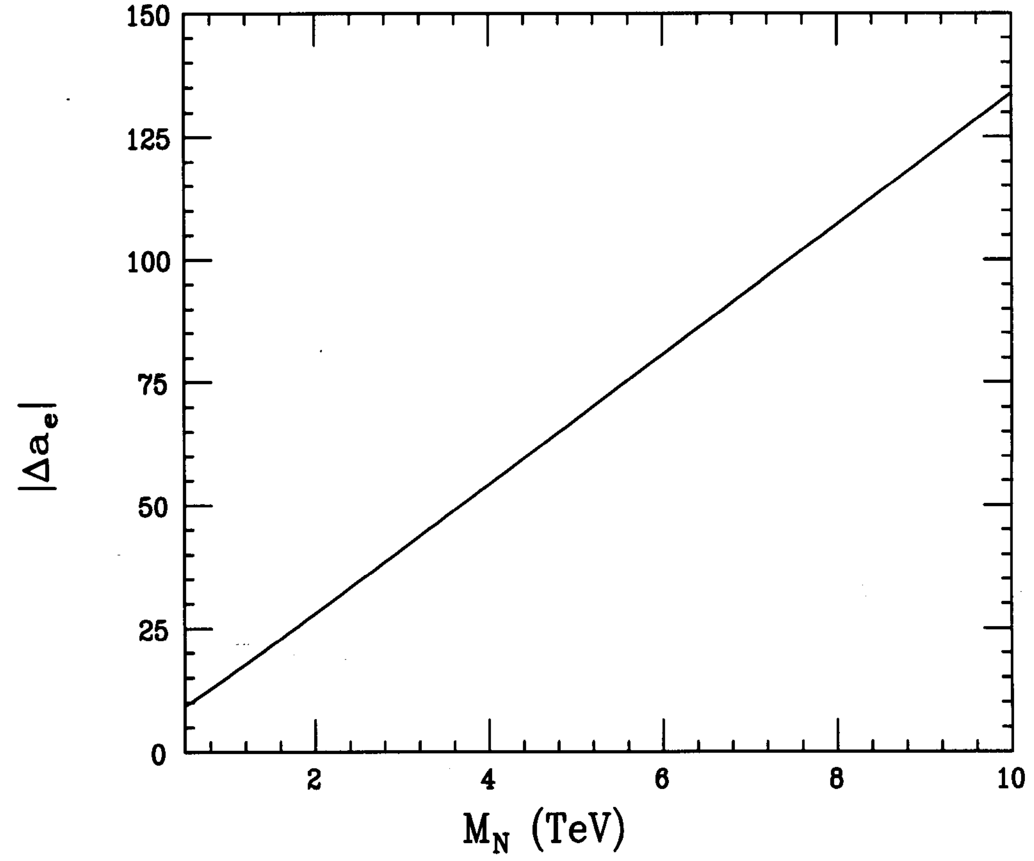


Figure 3: Contribution to the anomalous magnetic moment of the electron in model B in units of 10^{-12} due to mixing between the SM and the vector-like fermions as a function of the N fermion mass.

the kinematic function is different and with the replacement $\sin\theta_R^e \to \sin\theta_R^\nu$. The result of this calculation is presented in Fig.4 and should be compared to the present experimental limit[21] of $|\kappa_\nu| \leq 180 \times 10^{-12}\mu_B$ at 90% CL from elastic $\bar{\nu}_e e$ elastic scattering using reactor neutrinos. Stronger bounds (by factors of order 10) based on astrophysical constraints remain somewhat controversial[21]. Note that a similar graph without the attached photon is capable of generating a mass for ν_e in the range $10^{-3} - 10^{-2}$ eV.

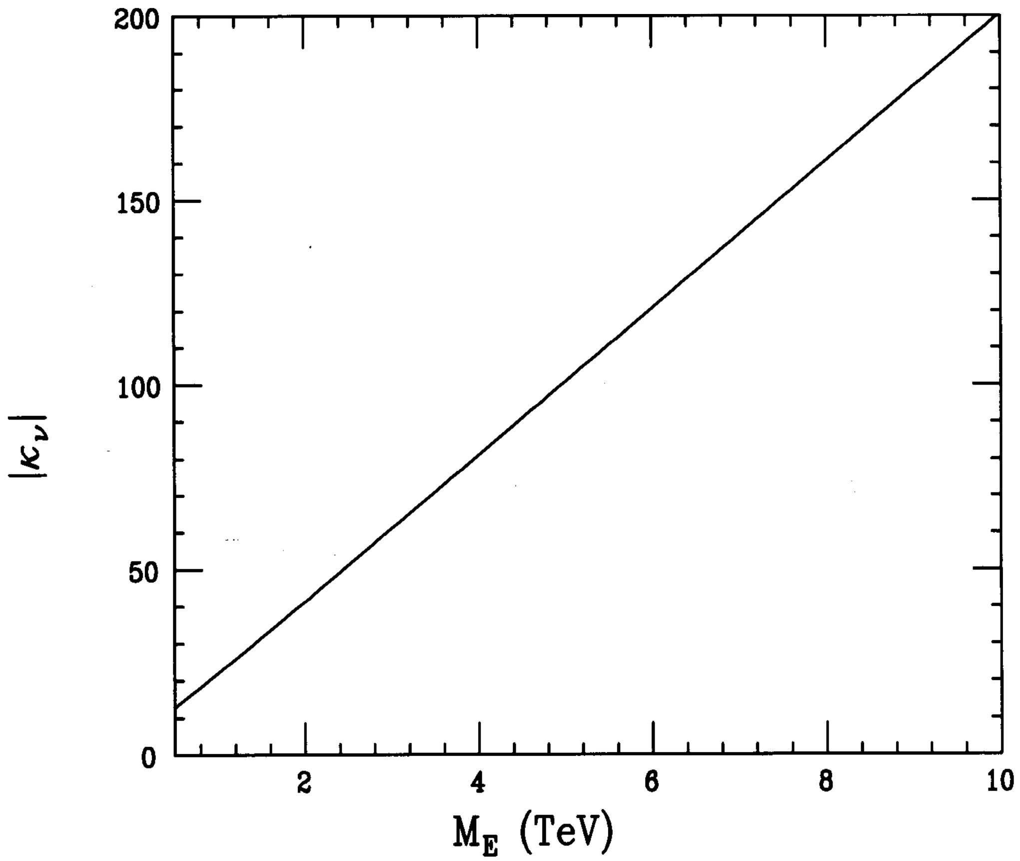


Figure 4: Mixing induced contribution to the magnetic moment of the electron neutrino in model B in units of 10^{-12} Bohr magnetons as a function of the E fermion mass.

3.4 *Oblique Parameters, Z Pole Observables, and APV*

Vector-like fermions are known to have negligible contributions[17] to the oblique parameters[18]. However, once vector-like fermions mix with their SM counterparts it is possible to induce non-zero shifts in the values of these parameters. As a numerical example, we examine the size of these contributions in model A. In the case of the shift in the ρ parameter, $\Delta\rho \equiv \alpha T$, there are two sources which contribute here: (i) the modification of both the vector-like and SM fermion couplings to the W and Z due to mixing; (ii) the U and D masses, originally degenerate, are now split by an amount $M_U^2 - M_D^2 = a_u^2 v^2 - a_d^2 v^{c2}$. Writing in this case $c_{u,d} = \cos\theta_R^{u,d}$ and $s_{u,d} = \sin\theta_R^{u,d}$, one obtains

$$\Delta\rho = \frac{3G_F}{8\sqrt{2}\pi^2}\left\{c_u^4 M_U^2 + c_d^4 M_D^2 - 2c_u^2 c_d^2 \frac{M_U^2 M_D^2}{M_U^2 - M_D^2} \ln\frac{M_U^2}{M_D^2}\right\}. \tag{21}$$

Note that when $c_u = c_d = 1$, $M_U = M_D$ and $\Delta\rho$ vanishes as expected. For $M_{U,D} \simeq 5$ TeV and $\theta_R^{u,d} \simeq 0.05$, $\Delta\rho$ is found to be $< 10^{-4}$, far too small to be observed. In a similar vein, the induced value for the parameter S is found to be less than 5×10^{-4} and is hence also vanishingly small. Thus, although the vector-like fermions do not remain purely vector-like after mixing, their contribution to the oblique parameters remain negligible. This same pattern is repeated in the case of the other models with only minor differences, *e.g.*, color factors are present in the case of model B and the gauge invariant mass terms for the two isosinglet fields in either models CD or EF can be different. Numerically, however, similarly small results are obtained for the oblique parameters in these remaining models.

Are there observable modifications in the SM fermion couplings to the Z-boson? Recall that, for example, the mixing of the u and d quarks with vector-like fermions which have weak isospin $T'_{3u,3d}$ produces a shift in the u and d couplings to the Z of $\Delta v_u(a_u) = (T'_{3u} - 1/2)(s_L^u)^2 \pm T'_{3u}(s_R^u)^2$ and $\Delta v_d(a_d) = (T'_{3d} + 1/2)(s_L^d)^2 \pm T'_{3d}(s_R^d)^2$, respectively, using the notation above. (The corresponding shifts in the case of leptonic mixing can be obtained from these expressions by trivial notational changes.) Two places where these coupling shifts may show up most clearly are in the partial widths of the Z-boson and in APV. In both these observables there is an additional shift in the case of the leptonic couplings due to the overall change in the coupling normalization from the redefinition of G_F from muon decay, as discussed above. However, the Z leptonic asymmetries, which are particularly important observables, are insensitive to these overall changes in the coupling normalization. For this case, taking the relevant mixing angle to be 0.05 as usual, we find that the Z partial width to the e^+e^- final state is decreased(increased) by an amount of order $\simeq$ 0.2 MeV for the isodoublet(isosinglet) model. Correspondingly, the apparent shift in the value of $\sin^2\theta_w^{eff}$ from the asymmetries increases(decreases) by an amount of order $\simeq$ 0.0006 for these same two cases. Both of these shifts are essentially at the boundary of the current level of sensitivity for LEP/SLD measurements[30]. Similarly there is a corresponding shift in the number of neutrinos extracted from the measurement of the Z invisible width by $\simeq$ 0.005.

These shifts in the SM fermion couplings can modify the expectations for APV as well since the effective weak charge, Q_w, directly probes the two products $a_e v_u$ and $a_e v_d$ in addition to the shift in the overall normalization that occurs with leptonic mixing. In the case where the SM fermions mix with their leptonic vector-like counterparts, the shift in Q_w is directly given by

$$\Delta Q_w/Q_w = \delta\rho - 2(T'_{3e}+1/2)(s^e_L)^2 + 2T'_{3e}(s^e_R)^2\,, \tag{22}$$

where $\delta\rho$ represents the change in the overall coupling normalization and is given to leading order in the mixing angles by

$$\begin{aligned} B &: (\theta^\nu_L - \theta^e_L)^2 - (\theta^\nu_R\theta^e_R)^2\,, \\ CD &: (\theta^\nu_L)^2 + (\theta^e_L)^2\,. \end{aligned} \tag{23}$$

We find that this fractional shift in Q_w is at the 10^{-3} level for either isosinglet or isodoublet leptonic vector-like fermions and is hence clearly too small to be observed. The modification could be potentially larger when mixing occurs in the u and d couplings and where there is no overall change in the normalization. However we find that the individual contributions of the u and d quarks tend to cancel each other instead of adding coherently, leaving, again, a relative shift in Q_w at the 10^{-3} level.

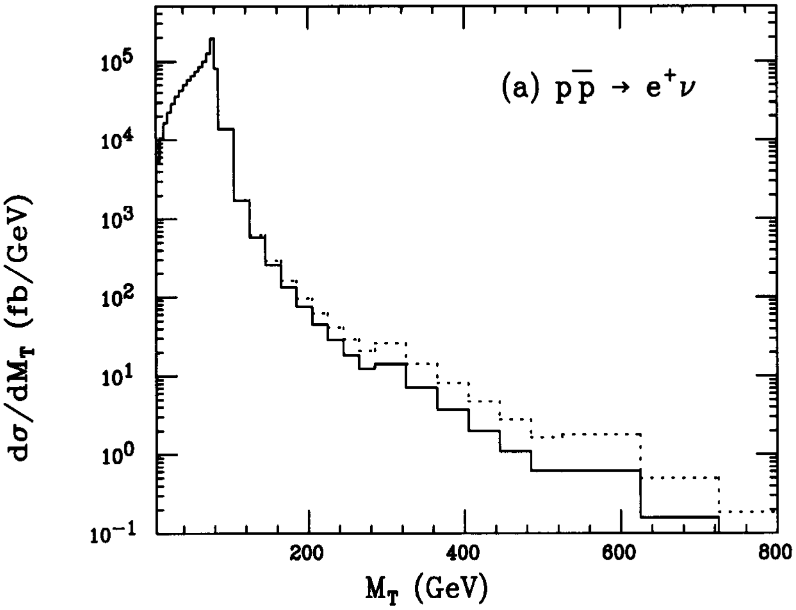
3.5 *Drell-Yan Production in the $e^{\pm}\nu_e$ Channel*

What future constraints can be placed on the leptoquark couplings? We know from earlier work[8] that the λ_d coupling can be probed in high precision measurements at LEP II in $e^+e^- \to q\bar{q}$ and also at the Tevatron via NC Drell-Yan production. Can future colliders also probe the λ_u coupling? One possibility is to examine the corresponding CC Drell-Yan process at hadron colliders, $p\overset{(}{\bar{p}}\overset{)}{} \to e^{\pm}\nu$. In addition to the usual SM W-boson exchange, leptoquarks can also contribute to this process via t-channel exchange involving both the λ_d and λ_u couplings. The subprocess cross section for this reaction is found to be

$$\frac{d\hat{\sigma}(\bar{u}d \to e^-\bar{\nu}_e)}{dz} = \frac{G_F^2 M_W^4}{12\pi\hat{s}} \left[\frac{\hat{u}^2}{(\hat{s}-M_W^2)^2 + (\Gamma_W M_W)^2} + \left(\frac{\tilde{\lambda}_u\tilde{\lambda}_d}{x}\right)^2 \frac{\hat{t}^2}{(\hat{t}-m_{LQ}^2)^2} \right], \tag{24}$$

where $x = G_F M_W^2/2\sqrt{2}\pi\alpha$ and $z = \cos\theta^*$, the parton center of mass scattering angle between the incoming quark and the outgoing negatively charged electron; as usual $\hat{t} = -\hat{s}(1-z)/2$ and $\hat{u} = -\hat{s}(1+z)/2$. Note that there is no interference between the W-boson and leptoquark exchanges which will make the leptoquark contribution somewhat more difficult to observe although the two distributions peak in opposite angular regions.

There are two useful observables in this case. First, one can examine the transverse mass (M_T) distribution beyond the Jacobian peak associated with W-boson production. For



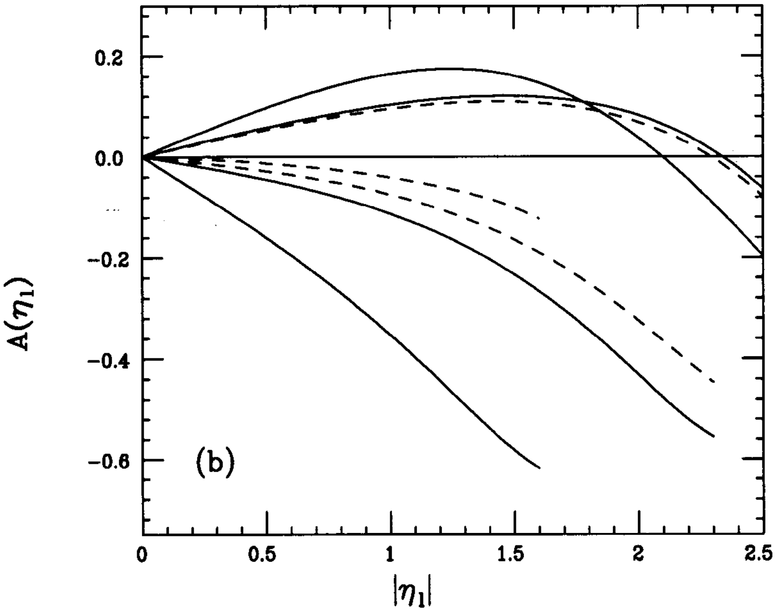


Figure 5: (a) The electron plus neutrino transverse mass distribution assuming $|\eta_\ell| \leq 2.5$ and (b) the folded lepton charge asymmetry in the charged current Drell-Yan production channel at the 2 TeV Tevatron for the SM (solid curves)and with 200 GeV scalar leptoquark exchange assuming $\tilde{\lambda}_u\tilde{\lambda}_d = 1$(dashed curves). In (b), from top to bottom in the center of the figure, the SM curves correspond to M_T bins of 50-100, 100-200, 200-400 and $>$ 400 GeV, respectively. Note that for M_T in the 50-100 GeV range there is no distinction between the SM result and that with a leptoquark.

large values of M_T one would expect an increase in $d\sigma/dM_T$ due to the leptoquark exchange. A second possibility is to examine the leptonic charge asymmetry, $A(\eta_\ell)$, for the case of electrons in the final state as a function of their rapidity. Here $A(\eta_\ell)$ is defined as

$$A(\eta_\ell) = \frac{dN_+/d\eta_\ell - dN_-/d\eta_\ell}{dN_+/d\eta_\ell + dN_-/d\eta_\ell}\,, \tag{25}$$

where $N_\pm$ are the number of positively/negatively charged electrons of a given rapidity. In the SM, the charge asymmetry is sensitive to the ratio of u-quark to d-quark parton densities and the $v-a$ structure of the W decay[31]. Since the decay structure of the W has been well-measured elsewhere[32], any observed deviations from SM expectations in this asymmetry have been attributed to modifications in the parton density functions[33]. The possibility of new physics contributing to this channel has been overlooked. In calculating the asymmetry it is essential to split the integration over the parton densities into 2 regions, corresponding to positive and negative lepton rapidities in the W center of mass frame, according to the prescription in Ref. [34]. Fig.5 shows how both the binned transverse mass distribution and the lepton charge asymmetry, for four M_T bins corresponding to $50 < M_T < 100$ GeV, $100 < M_T < 200$ GeV, $200 < M_T < 400$ GeV, and $400 < M_T$ GeV, are modified by the presence of a 200 GeV leptoquark with, for purposes of demonstration, $\tilde{\lambda}_u\tilde{\lambda}_d = 1$. We see that the transverse mass distribution does rise above the SM expectations for large values of M_T as expected, and that the lepton charge asymmetry can also be significantly modified for larger values of M_T. Note that there is little deviation in the asymmetry in the transverse mass bin associated with the W peak, $50 < M_T < 100$ GeV, so that this M_T region can still be used for determination of the quark densities.

We now perform a χ^2 analysis to determine the potential sensitivity to leptoquark exchange at the main injector. As shown in Fig.5(a), we divide the transverse mass distribution into several bins corresponding to

$$\begin{array}{rcl} \text{7 bins in steps of 5 GeV in the range} & 50 \leq M_T \leq 85 & \text{GeV}\,, \\ \text{10 bins in steps of 20 GeV in the range} & 85 \leq M_T \leq 285 & \text{GeV}\,, \\ \text{6 bins in steps of 40 GeV in the range} & 285 \leq M_T \leq 525 & \text{GeV}\,, \\ \text{2 bins in steps of 100 GeV in the range} & 525 \leq M_T \leq 725 & \text{GeV}\,, \\ \text{1 bin for the range} & 725 \leq M_T & \text{GeV}\,. \end{array} \tag{26}$$

This ensures that adequate statistics are maintained in each bin. The apparent rise in the cross section in Fig. 5(a) at $M_T = 285$ GeV is an artifact of the increased bin width at that point. For the lepton charge asymmetry the lepton's rapidity is binned as

$$\begin{array}{rcl} \text{12 bins in steps of } \Delta\eta_\ell = 0.2 \text{ in the range} & 50 \leq M_T \leq 100 & \text{GeV}\,, \\ \text{12 bins in steps of } \Delta\eta_\ell = 0.2 \text{ in the range} & 100 \leq M_T \leq 200 & \text{GeV}\,, \\ \text{6 bins in steps of } \Delta\eta_\ell = 0.3 \text{ in the range} & 200 \leq M_T \leq 400 & \text{GeV}\,, \\ \text{2 bins of } |\Delta\eta_\ell| \leq 0.4 \text{ and } |\Delta\eta_\ell| \geq 0.4 \text{ in the range} & 400 \leq M_T & \text{GeV}\,, \end{array} \tag{27}$$

subject, of course, to the constraint $M_T \leq \sqrt{s}e^{-|\eta_\ell|}$. We note again, that there is no sensitivity to the leptoquark exchange on the W transverse mass peak ($50 < M_T < 100$ GeV), and hence this region does not contribute to the χ^2 distribution. The bin integrated cross section and asymmetry are then obtained for the SM and for the case of 200 GeV scalar leptoquark exchange. We sum over both $e^+\nu_e$ and $e^-\bar{\nu}_e$ production for the cross section and employ an electron identification efficiency of 0.75. The statistical errors are evaluated as $\delta N = \sqrt{N}$ and $\delta A = \sqrt{(1-A^2)/N}$, as usual. The resulting 95% C.L. bound in the $B_\ell - \tilde{\lambda}_d$ plane is presented in Fig. 6 for 2 and 30 fb^{-1} of integrated luminosity with $\sqrt{s} = 2$ TeV. We see that even for 30 fb^{-1}, the constraints are inferior to those obtained from present data on π decay universality as shown in Fig. 2.

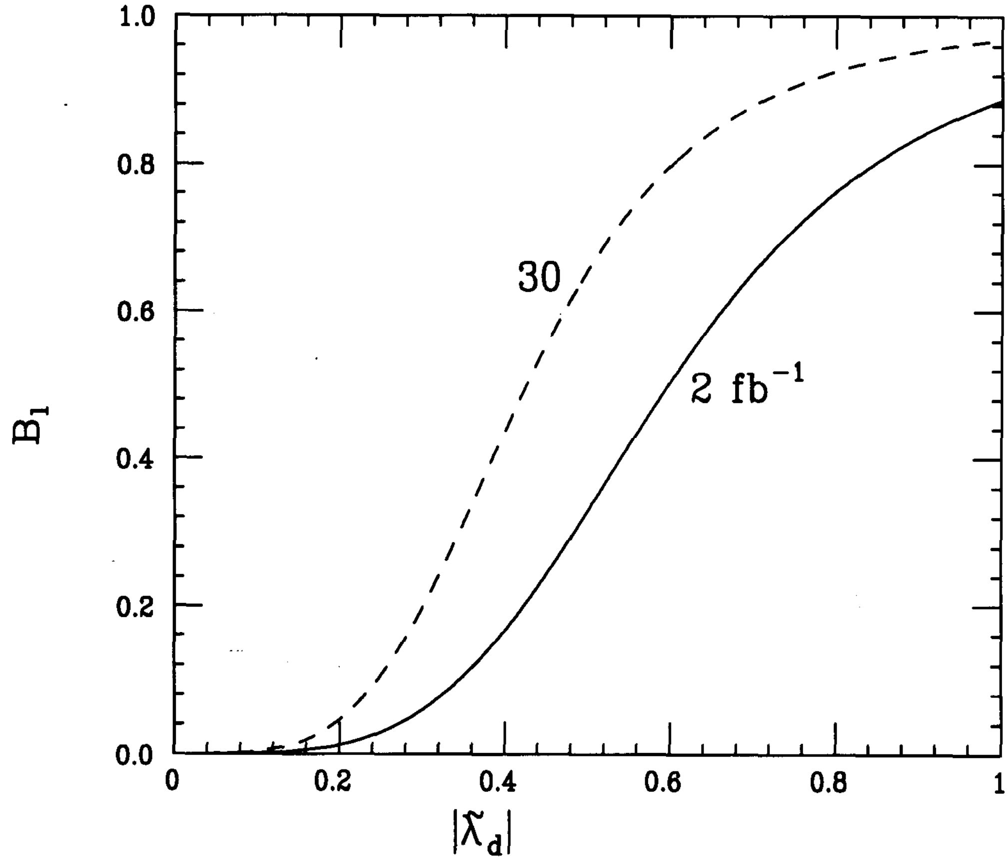


Figure 6: 95% CL bound on B_ℓ as a function of $\tilde{\lambda}_d$ from a fit to both the M_T distribution and $A(\eta_\ell)$ at the 2 TeV Tevatron for two integrated luminosities as indicated. The area below and to the right of the curves are excluded.

3.6 *Like-Sign Leptoquark Production at the Tevatron*

In models B and C where the u quark couples to a heavy neutral vector-like fermion, N, new processes may arise if N is a Majorana field. (Note that for simplicity we have only considered the Dirac case in the above discussions.) One such unusual possibility is the production of pairs of *identical* leptoquarks in hadronic collisions via $u-$ or $t-$channel N exchange which generates the process $uu \to 2LQ$. The leptoquarks then decay to like-sign charged leptons plus jets, a relatively clean signature at a hadron collider. Recall that the relevant Yukawa coupling involved in this $\Delta L = 2$ reaction is of order unity so that this cross section may be significant even though it is a valence times sea-quark density process at the Tevatron. We find the subprocess cross section to be

$$\frac{d\sigma}{dz} = \frac{\lambda^4}{128\pi}\beta\left[\frac{M_N(\hat{t}+\hat{u}-2M_N^2)}{(\hat{t}-M_N^2)(\hat{u}-M_N^2)}\right]^2 , \tag{28}$$

where $\lambda \sim 1$, z is defined in the previous section, and M_N is the mass of the neutral vector-like fermion. Here, $\hat{t} = -\hat{s}(1-\beta z)/2$ and $\hat{u} = -\hat{s}(1+\beta z)/2$, where $\beta = (1-4m_{LQ}^2/\hat{s})^{1/2}$. Note that as $M_N \to 0$ the cross section vanishes as expected for a Majorana fermion induced process. The rate for this reaction at the Tevatron with $\sqrt{s}$=2 TeV is shown in Fig.7 for $\lambda = 1$. Here we see that the cross section initially rises with increasing M_N but then begins to fall, scaling like M_N^{-2} as $M_N \to \infty$. For M_N=1 TeV, this cross section corresponds to $\simeq$ 100 events at the Main Injector *before* leptoquark branching fractions are taken into account. At the $\sqrt{s}$=1.8 TeV collider the cross section is smaller by a factor of $\simeq 0.56$.

3.7 *Speculations on a Realistic Flavor Coupling Structure*

Although one can impose discrete or other symmetries so that leptoquarks only couple to a single generation in the weak eigenstate basis it is difficult to understand how this might

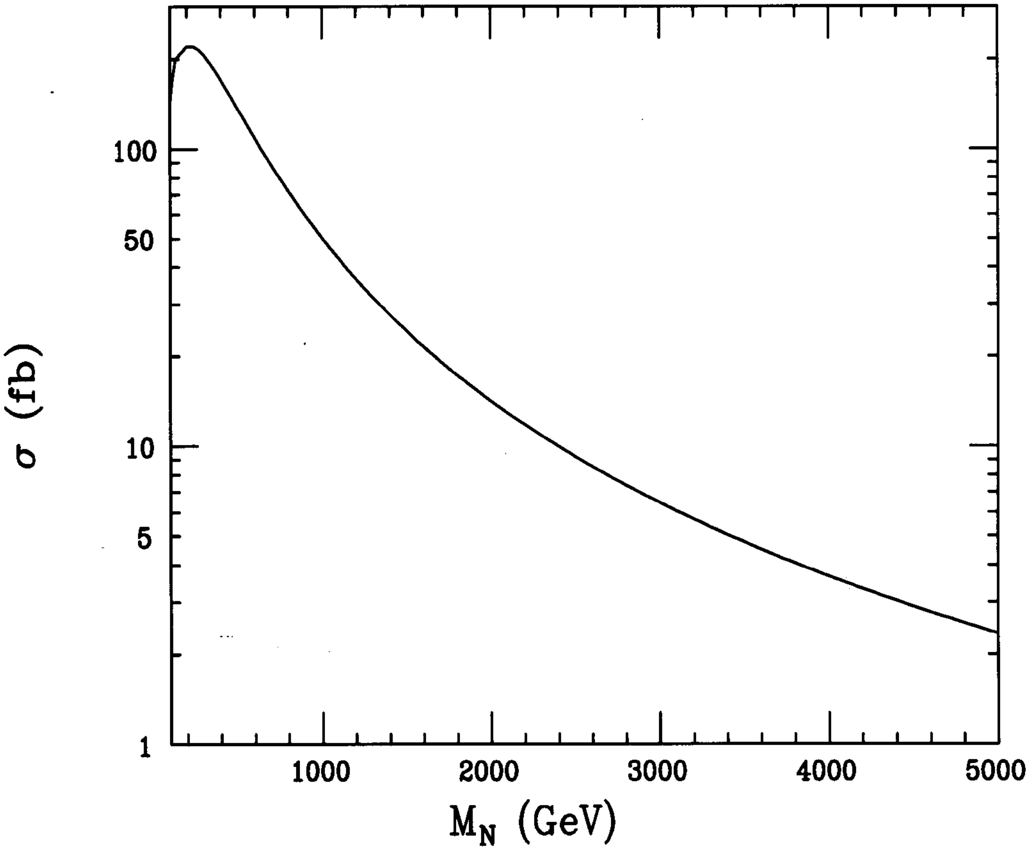


Figure 7: Cross section for like-sign pairs of 200 GeV leptoquarks at the 2 TeV Tevatron as a function of the neutral vector-like fermion mass, M_N. The Yukawa coupling is assumed to be unity.

hold in the physical basis. This issue is a major stumbling block for the construction of realistic leptoquark models and is one that we have carefully avoided until now. Of course the detailed exploration of possible solutions to this problem lies outside the scope of this paper[35], however, there are directions that do show some promise[36].

To be more specific, let us concentrate on models which yield the interaction $\mathcal{L}_{wanted}$ in Eq. (1) where the ν^c field is absent, and also neglect the possibility of any large leptonic mixing. This implies that all of the traditional flavor changing neutral current (FCNC) constraints are only to be applied to the quark sector of the model as lepton number is conserved. Interestingly, in this case the relevant flavor changing terms are induced by the right-handed unitary matrices $U(u,d)_R$ of which there is no information since they play no role in SM interactions. For purposes of demonstration we will this simply assume that element for element they are numerically similar to the corresponding CKM matrix elements. Thus flavor mixing now leads us to make the substitutions $u_R \to \sum_i [U(u)_R]_{1i}(u_R)_i$ and similarly for d_R in $\mathcal{L}_{wanted}$. This particular form guarantees that tree level $s \to d$ and $b \to d, s$ transitions will be accompanied by e^+e^-, while $c \to u$ processes are accompanied only by $\bar{\nu}_e\nu_e$. Thus leptoquarks will not mediate the potentially dangerous processes $K \to \pi\bar{\nu}\nu$ or $D \to \pi e^+e^-$ at tree level.

Are the tree-level rates induced by these leptoquarks dangerously large? Fortunately, the chirality of the leptoquark couplings automatically reduces the size of their potential contributions to rare processes and the fundamental couplings present in the Lagrangian are already quite small. As we saw from our discussion of $|V_{ud}|$, for example, the effective Fermi coupling for leptoquark exchange was below the level of $10^{-3}G_F$ for typical values of the Yukawa couplings. In fact, using $\tilde{\lambda}_{u,d} \simeq 0.15$ and $M_{LQ} = 200$ GeV it is easy to show that this class of models indeed satisfies all of the FCNC experimental constraints in Ref. [36] for values of $[U(d)_R]_{sd}$, $[U(u)_R]_{uc}$ of order 0.1-0.2. (This result remains true even when these constraints are strengthened by more recent experimental results[21]). This observation leads us to believe that leptoquarks of the type under discussion here are not only compatible with present bounds from flavor changing data but may lead to new effects in flavor physics that are comparable in magnitude to SM contributions and can thus be searched for in charm or B factories[35].

4 Unification? Never Break the Chain

4.1 *Non-SUSY Case*

If leptoquarks exist and we also believe that there is experimental evidence for coupling constant unification then we must begin to examine schemes which contain both ingredients as pointed out in our earlier work[8]. In the scenarios at hand, the SM quantum numbers of the leptoquark are fixed but new vector-like fermions have now been introduced as well, all of which will alter the usual RGE analysis of the running couplings.

Before discussing supersymmetric models we note that coupling constant unification *can* occur in leptoquark models containing exotic fermions even if SUSY is not introduced as was shown many years ago in Refs. [37, 38]. Of course in the work of Murayama and Yanagida[37], the leptoquark was an isodoublet which was one of the BRW models, and is now excluded by the combined HERA and Tevatron data. In the scenarios presented here the leptoquark is now a $Q = 2/3$ isosinglet so that the Murayama and Yanagida analysis does not apply. Fortunately, we see from the results of Ref. [38] that a second unification possibility does exist for just these types of models: in addition to the SM spectrum, one adds a leptoquark and its conjugate as well as a vector-like pair of color-triplet, isodoublets together with the field H^c. This is just the particle content of model A. To verify and update this earlier analysis, we assume for simplicity that all the new matter fields are introduced at the weak scale and take $\sin^2\theta_w = 0.2315$ as input to a two-loop RGE study. The results are shown in Fig.8 where we obtain the predictions that coupling unification occurs at 3.5×10^{15} GeV and $\alpha_s(M_Z)$ is predicted to be 0.118. If unification does indeed occur we can estimate the proton lifetime[39] to be $\tau_p = 1.6 \times 10^{34\pm1}$ years, safely above current constraints[21]. We find this situation to be intriguing and we leave it to the reader to ponder further.

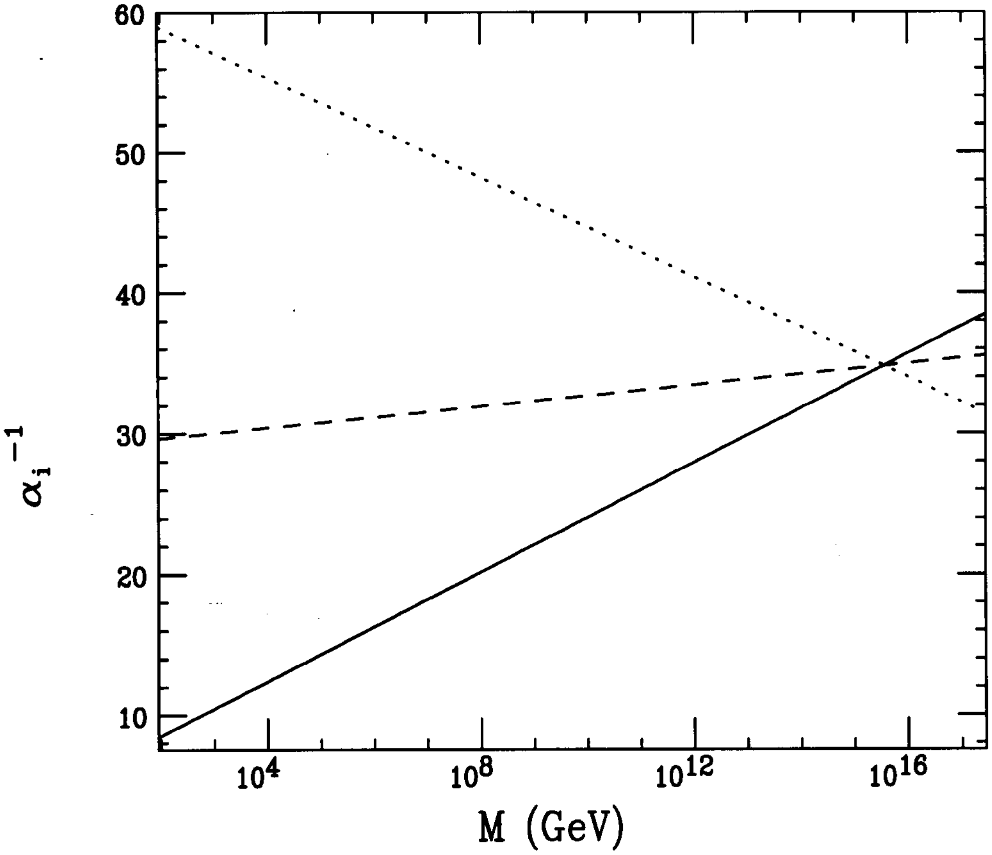


Figure 8: Two-loop RGE evolution of the model with the SM particle content together with a leptoquark and its conjugate as well as with the vector-like fermions and Higgs content of model A. The $SU(3)_C(SU(2)_L,\ U(1)_Y)$ coupling corresponds to the dotted(dashed, solid) curve.

4.2 *SUSY Models*

Of course there are other reasons to introduce SUSY beyond that of coupling constant unification, so we now turn to the SUSY versions of the above leptoquark models with the assumption that R-parity is preserved, *i.e.*, the HERA excess is due to a leptoquark and not a squark produced through R-parity violating interactions. This subject was discussed at some length in our earlier work[8] from a somewhat different viewpoint but from which we are reminded of several important points:

(*i*) To *trivially* preserve the successful unification of the SUSY-SM, only complete $SU(5)$ representations can be added to the conventional MSSM spectrum. As is well-known, the addition of extra matter superfields in complete $SU(5)$ representations delays unification and brings the GUT scale much closer to the string scale. Of course, there still remains the rather unnatural possibility of adding incomplete, but 'wisely chosen', split representations. This is what happens, of course, in the case of the usual Higgs doublets and is the basis for the famous doublet-triplet splitting problem. Employing split representations certainly allows more flexibility at the price of naturalness but still requires one to choose sets of $SU(3)_C \times SU(2)_L \times U(1)_Y$ representations which will maintain asymptotic freedom and perturbative unification. Of course one would still need to eventually explain why these multiplets were split. An example of this rather bizarre scenario is the possibility of adding a $(2,3)(1/6)$ from a **15** and a $(1,1)(1) \oplus (1,\bar{3})(-2/3)$ from a **10** to the spectrum at low energy[8]. Here the notation refers to the $(SU(3)_C, SU(2)_L)(Y/2)$ quantum numbers of the representation. We remind the reader that in this notation the leptoquark itself transforms as $(1,3)(2/3)$; the smallest standard $SU(5)$ representation into which the LQ + LQ^c can be embedded is a $\mathbf{10}\oplus\overline{\mathbf{10}}$, while in flipped-$SU(5) \times U(1)$[40], it can be placed in a $\mathbf{5}\oplus\overline{\mathbf{5}}$.

(*ii*) Since we only have vector-like fermions in our models, it is clear that only pairs of representations, $\mathbf{R}+\overline{\mathbf{R}}$, can be added to the MSSM spectrum in order to maintain anomaly cancelation. Of course this is also true for the leptoquark superfield in that both the LQ and LQ^c fields must now be present as discussed above.

(*iii*) To preserve perturbation theory and asymptotic freedom up to the GUT scale when adding complete representations, at most one $\mathbf{10}+\overline{\mathbf{10}}$ pair or three $\mathbf{5}+\overline{\mathbf{5}}$ pairs can be appended to the low energy spectrum of the MSSM apart from SM singlets. The reason for this is the general observation that if one adds more than three, vector-like, color triplet superfields to the MSSM particle content then the one-loop QCD beta function changes sign. Recall that the leptoquark itself already accounts for one of these color triplets. This same consideration also excludes the introduction of light exotic fields in higher dimensional $SU(3)_C$ representations. Complete $SU(5)$ representations larger than $\mathbf{10}+\overline{\mathbf{10}}$ are found to contribute more than this critical amount to the running of the QCD coupling which would then blow up long before the GUT scale is reached. Whether unification with strong coupling is possible has been considered elsewhere[41], but we disregard this possibility here.

These are highly restrictive constraints on the construction of a successful GUT scenario containing both vector-like fermions and leptoquarks and we see that none of the models discussed above can immediately satisfy them *unless* the leptoquark and vector-like fermion superfields can be placed into a single $SU(5)$ representation. In the standard $SU(5)$ picture, we can then place $(U,D)^T$, an isosinglet E^c and LQ^c into a single $\mathbf{10}$ with the corresponding conjugate fields in the $\overline{\mathbf{10}}$. This would form a hybrid of model A with the 'skeleton' model D, which we have denoted by AD in Table 1. Of course we pay no penalty for also including the 'skeleton' model C here as well, which then yields model ADC. Instead, when we consider the flipped-$SU(5)\times U(1)$ case, it would appear that we can place $(N,E)^T$ and LQ^c into a $\overline{\mathbf{5}}$ with the conjugate fields in the $\mathbf{5}$; this is exactly model B. It would also seem that no penalty is paid as far as unification is concerned for including the 'skeleton' model C here as well *except* that this would violate our assumption about the chirality of leptoquark couplings to fermions. However, this model is no longer truly unified since the hypercharge generator is not fully contained within the $SU(5)$ group itself and lies partly in the additional $U(1)$. While the $SU(3)_C$ and $SU(2)_L$ couplings will unify, $U(1)_Y$ will not join them even when arbitrary additional vector-like singlet fields are added. Thus unification no longer occurs in this scenario so that this possibility is now excluded.

The leptoquark embedding situation becomes more perplexing if the leptoquark and vector-like fermions cannot occupy the same GUT multiplet. In this case unification and asymptotic freedom constraints become particularly tight and we are forced to consider the split multiplet approach mentioned above. This means that we add the fields $(2,3)(1/6) \oplus (1,1)(1) \oplus (1,\bar{3})(-2/3)$ and their conjugates at low energies but constrain them to be from different $SU(5)$ representations. In this case the combination $(1,3)(2/3) \oplus (1,\bar{3})(-2/3)$ corresponds to the isosinglet leptoquark and its conjugate so what remains can only be the vector-like fermion fields. Note that we have again arrived back at models AD and ADC. Are these the only solutions? We have performed a systematic scan over a very large set of vector-like fermions with various electroweak quantum numbers under the assumption that they are either color singlets or triplets, demanding only that (*i*) QCD remains asymptotically free and (*ii*) the model passes the so-called "B-test"[42] which is highly non-trivial to arrange. Essentially the B-test takes advantage of the observation that if we know the couplings at the weak scale and we demand that unification takes place *somewhere* then the values of the one-loop beta functions must be related. Note that it is a necessary but not sufficient test on our choice of models but is very useful at chopping away a large region of parameter space. Using the latest experimental data[30], we find that

$$B = \frac{b_3 - b_2}{b_2 - b_1} = 0.720 \pm 0.030\,, \tag{29}$$

where the ±0.030 is an estimate of the corrections due to higher order as well as threshold effects and the b_i are the one-loop beta functions of the three SM gauge groups. Note that $B_{MSSM} = 5/7 \simeq 0.714$ clearly satisfies the test. If we require that (*i*) and (*ii*) be satisfied and also require that the unification scale not be too low then only the solutions described above survive after examining $> 7 \times 10^7$ combinations of matter representations. While not completely exhaustive, this search indicates the solutions above are fairly unique. It is interesting to observe that models constructed around model A produce successful grand unification both with and without SUSY.

Finally we need to briefly comment on the possible relationship between the LQ and LQ^c masses and their SUSY partners. In these SUSY models one might imagine that the fermionic partner of the leptoquark, the leptoquarkino, may have a mass comparable to the vector-like fermions, *i.e.*, of order 1-5 TeV or so. Why then is the leptoquark itself so light? One possible mechanism, discussed in another context by Deshpande and Dutta[7], is to envision a large mixing between the leptoquark and its conjugate that produces a see-saw effect analogous to what happens in light stop quark scenarios[43]. This possibility will not be pursued further here.

5 Summary and Conclusions

In this paper, we have obtained a general framework for the construction of new $F = 0$ scalar leptoquark models which go beyond the original classification by Buchmüller, Rückl and Wyler. This approach is based on the observation that in any realistic extension of the SM containing leptoquarks it is expected that the leptoquarks themselves will not be the only new ingredient. This construction technique is, of course, far more general than that required to address the specific issue of the HERA excess and, as outlined, can also be used to obtain a new class of $F = 2$ scalar leptoquark models if so desired.

To extend leptoquark models into new territories it is necessary to re-examine the assumptions that have gone into the classic BRW framework. While the assumptions of gauge invariance and renormalizability are unquestionable requirements of model building, it is possible that the other conditions one usually imposes are much too strong–unless they are clearly demanded by data. This observation implies that for leptoquarks to be experimentally accessible now, or anytime soon, their couplings to SM fermions must be essentially chiral and separately conserve both Baryon and Lepton numbers. The assumption that leptoquarks couple to only a single SM generation is surely convenient by way of avoiding numerous low energy flavor changing neutral current constraints but is far from natural in the mass eigenstate basis. Our analysis indicates that the natural imposition of this condition in the original weak basis, and then allowing for CKM-like intergenerational mixing does not obviously cause any difficulties with experimental constraints, especially if lepton generation number is at least approximately conserved. What is required to obtain a new class of leptoquark models is that the leptoquarks themselves must be free to couple to more than just the SM fermions and gauge fields.

Given the fixed gauge structure of the SM the most likely new interactions that leptoquarks may possess are with the Higgs field(s) responsible for spontaneous symmetry breaking and with new vector-like fermions that are a common feature in many extensions of the SM. Such particles have the advantages that are automatically anomaly free and give essentially no significant contributions to the oblique parameters. In the analysis presented above we have shown how two particular new forms of the effective interactions of leptoquarks with the SM fermions, consistent with Tevatron searches, the HERA excess in both the NC and CC channels and low-energy data, can arise through the action of vector-like fermions and ordinary symmetry breaking. The typical vector-like fermion mass was found to lie in the low TeV region and they could thus be directly produced at future colliders with known rates. With our set of assumptions, we obtained ten new models which fell into two broad classes according to the chirality of the resulting leptoquark couplings to the SM fermions. The vector-like fermions themselves were shown to lead to a number of model-dependent effects which are close to the boundary of present experimental sensitivity including (*i*) violations of quark-lepton universality (for which, as discussed, there is some evidence at the 2σ level arising from the CKM matrix), (*ii*) possible small changes in the Z-pole observables for electrons, (*iii*) a small contribution to the shift in the value of the weak charge measured by atomic parity violation experiments over and above that induced by the leptoquark itself, (*iv*) a new contribution to the anomalous magnetic moments of the electron and electron neutrino, and (*v*) the possible production of like-sign leptoquarks with a reasonable cross section at the Main Injector. We also showed that, as in the case of Drell-Yan in the e^+e^- channel at the Tevatron discussed in our earlier work, there is some potential sensitivity to $t-$channel leptoquark exchange in the corresponding $e^{\pm}\nu$ channel through the transverse mass distribution and the charged lepton asymmetry.

Leptoquarks within the framework of models containing vector-like fermions were shown to be consistent with Grand Unification in both a supersymmetric *and* non-supersymmetric context. The common feature of both schemes is the structure associated with model A, *i.e.*, the vector-like fermions are color triplet, weak isodoublets in a $(2,3)(1/6)$ representation and both H and H^c Higgs fields are required to be present as is LQ^c field. In both scenarios the GUT scale is raised appreciably from the corresponding model wherein leptoquarks and vector-like fermions are absent. In the SUSY case a $(1,1)(1)$ field is also required with the optional addition of a SM singlet, corresponding to models AD and ACD. In some sense, ACD is the "anti-E_6" model in that the color triplet vector-like fermions are in isodoublets while the color singlet fields are all isosinglets. Interestingly, in this scenario there is a vector-like fermion corresponding to every type of SM fermion.

Realistic leptoquark models provide a rich source of new physics beyond the Standard

Model.

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