Implications of a charged-current anomaly at HERA$^1$

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Abstract

We demonstrate that in the presence of mixing between different scalar leptoquark multiplets it is possible to simultaneously account for the HERA high-$Q^2$ neutral current anomaly, and produce a charged current anomaly of comparable magnitude. The reduced branching ratio to electrons and jets of the lightest leptoquark state results in a significant weakening of the CDF/D0 limits on scalar leptoquarks; masses consistent with the HERA neutral current excess are comfortably within the allowed range. We show that the possibilities for such a successful mixed leptoquark scenario are quite limited, and we investigate some aspects of their phenomenology.

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1 Introduction

The H1 [1] and ZEUS [2] collaborations at HERA recently announced an anomaly at high-$Q^2$ in the $e^+p \rightarrow eX$ neutral current (NC) channel. With a combined luminosity of 34.3 pb$^{-1}$ in $e^+p \rightarrow eX$ mode at $\sqrt{s} = 300$ GeV, the two experiments observe 24 events with $Q^2 > 15000$ GeV$^2$ against a Standard Model (SM) expectation of 13.4 $\pm$ 1.0, and 6 events with $Q^2 > 25000$ GeV$^2$ against an expectation of only 1.52 $\pm$ 0.18. The high-$Q^2$ events seem to be clustered at Bjorken-$x$ values near 0.4 to 0.5, with the H1 data showing a more pronounced peak.

HERA is capable of running in two modes: $e^-p$ and $e^+p$. In the former mode H1 and ZEUS have accumulated 1.53 pb$^{-1}$ of data but have observed no statistically significant deviations from the SM. Further, the experiments differentiate between final state $eX$ and $\nu X$, where the neutrino is detected through its missing $p_T$. H1 has also announced its findings in the $e^+p \rightarrow \nu X$ charged current (CC) channel. They find 3 events at $Q^2 > 20000$ GeV$^2$ with an expectation of 0.74 $\pm$ 0.39, but no events with $Q^2 > 25000$ GeV$^2$. ZEUS has not announced its CC data. Compared to the NC channel, the present CC signal is considerably less statistically significant. However, if the current trend persists in the 1997 HERA data, there will be interesting constraints on theoretical interpretations of the HERA excess.

There are three general categories of explanation for the NC excess: (1) a statistical fluctuation, (2) unexpected SM physics, for example, a modification of the parton distribution functions of the proton at moderate-to-high-$x$ and large $Q^2$, or (3) new physics.

For case (1) we have nothing to say. The possibility of modifying the parton distribution functions (2) was suggested in [3], and its consequences for the high-$Q^2$ HERA NC and CC data were studied in [4]. This suggestion has the advantage that it is relatively conservative, and furthermore automatically avoids the serious flavor problems [3, 4, 5] associated with most new physics explanations. However the most attractive hypothesis for modifying the parton distribution functions, the (symmetric) intrinsic charm scenario, has already been shown to be inconsistent with the high-$Q^2$ HERA data itself [4].

In category (3) are a variety of forms the new physics could take. These include contact interactions [1, 2, 3], $s$-channel production of a leptoquark or a squark with $R$-parity violating interactions [4, 5], and related proposals [6].

In this paper we consider the implications of the present and future HERA CC data for new physics. The constraints on, and the consequences of, contact interactions for the CC data has been considered by Altarelli, et al [7]; there they found that it was very difficult to explain any excess in the CC comparable to that in the NC. They also considered CC signals in scenarios with leptoquarks, with emphasis on the supersymmetric $R$-parity violating case. For the case of leptoquarks they were able to find scenarios with a significant CC excess. In this paper we will also consider leptoquarks, but unlike Ref. [7], we will examine the consequences of leptoquark
Table 1: List of scalar leptoquark operators. For each operator, the $SU(3) \times SU(2) \times U(1)$ quantum numbers of the leptoquark, $\Phi$, are shown. The fifth column indicates whether HERA should find CC events, and the final column lists the mode in which HERA should dominantly produce the given leptoquark. $Q$ and $L$ represent $SU(2)$ doublet quarks and leptons, while $e$, $u$ and $d$ are $SU(2)$ singlets.

| Operator | SU(3) | SU(2) | U(1) | CC mode |
|----------|-------|-------|------|---------|
| $L^i Q^j \Phi'_{LQ} \epsilon_{ij}$ | $\bar{3}$ | 1 | 1/3 | Yes $e^-$ |
| $\bar{L}^i Q^j (\Phi_{LQ})_{ij}$ | $\bar{3}$ | 3 | 1/3 | Yes $e^-$ |
| $\bar{L}^i \pi^j \Phi'_{Ld} \epsilon_{ij}$ | 3 | 2 | 7/6 | No $e^+$ |
| $\bar{L}^i d^j \Phi'_{Ld} \epsilon_{ij}$ | 3 | 2 | 1/6 | No $e^+$ |
| $\bar{\tau}^i e^j \Phi'_{Le} \epsilon_{ij}$ | $\bar{3}$ | 2 | $-7/6$ | No $e^+$ |
| $\bar{\tau}^i u^j \Phi'_{Le} \epsilon_{ij}$ | 3 | 1 | $-1/3$ | No $e^-$ |
| $\bar{\tau}^i d^j \Phi'_{Le} \epsilon_{ij}$ | 3 | 1 | $-4/3$ | No $e^-$ |

m1:

ing on the CC signal and demonstrate that comparable CC and NC excesses can similarly be obtained. We also investigate the consequences of leptoquark mixing for low-energy precision measurements, and for high-energy direct searches at the Tevatron. In this regard, one noteworthy feature of scenarios with a CC signal is that the recent CDF/D0 leptoquark limits [15, 16, 17] (for scalar leptoquarks $M > 210$ GeV at 95% C.L.) are considerably weakened.

If the NC anomaly at HERA is explained by $s$-channel production of a scalar leptoquark then the measured Bjorken-$x$ distribution translates into a mass determination: $m^2 = xs$. For both H1 and ZEUS two independent determinations are possible, depending on whether $x$ is calculated from the double-angle or electron methods. For the seven events selected for special study by H1 we find these two methods give $M_{2\alpha} = 202 \pm 14$ GeV and $M_e = 199 \pm 8$ GeV respectively. Similarly, for the five events selected by ZEUS, $M_{2\alpha} = 231 \pm 16$ GeV and $M_e = 219 \pm 12$ GeV. Similarly, the 3 highest-$Q^2$ events in the H1 CC data are also clustered in $x$ yielding $M_{CC} = 197 \pm 20$ GeV, where the error is dominated by the H1 energy resolution. The fact that the CC and NC mass determinations at H1 so closely match supports the hypothesis that both anomalies are coming from production of the same particle, which then decays either to electrons or neutrinos.

2 Mixing of scalar leptoquarks

We will argue in this section that although with a single scalar leptoquark multiplet one does not expect a charged-current signal at HERA, in the presence of mixing of different leptoquark multiplets a charged-current signal is possible.

The possible renormalizable couplings of scalar leptoquarks to SM fermions are enumerated in Table 1 [5], along with their $SU(3) \times SU(2) \times U(1)_Y$ quantum numbers. We will consider only $s$-channel production of leptoquarks. (It was shown in [5] that
$u$-channel exchange of a light leptoquark could not consistently explain the HERA NC data.) If the NC events at HERA are due to an $s$-channel leptoquark, then the scattering of the $e^+$ must be off one of the valence quarks in the proton. Operators satisfying this constraint are listed as “$e^+$” mode in the last column of the table. On the other hand, leptoquarks in the remaining “$e^-$” operators are dominantly produced in $e^-$ mode, and would have been already detected in HERA’s $e^-p$ data (even with the much smaller accumulated luminosity) given the size of coupling necessary to explain the anomaly in the $e^+p$ data. The reason for this is that the leptoquarks in “$e^-$” operators are produced by scattering off sea quarks in $e^+p$ mode, but off valence quarks when HERA runs in $e^-p$ mode. Finally, in the column “CC” is indicated whether or not the operator leads, in the absence of mixing, to CC events at HERA in addition to the NC. We see that the three allowed types of scalar leptoquark are all SU(2) doublets, and cannot lead to a CC signal at HERA in either $e^+p$ or $e^-p$ mode.

However, as we now argue, in the presence of mixing, these three operators can lead to a CC signal comparable in magnitude to the NC signal. If we wish to simultaneously explain an excess in both the NC and CC channels, then the mixing must involve at least one of the following leptoquark states: (i) the charge $Q = 2/3$ component of $\Phi_{Ld}$, (ii) the $Q = 5/3$ component of $\Phi_{Lu}$, and (iii) either the $Q = -5/3$ or the $Q = -2/3$ components of $\Phi_{eQ}$. These components can mix with other leptoquark states or with each other.

The most important constraint on such mixing arises from the necessity of avoiding helicity-unsuppressed rare decays. If a leptoquark couples significantly to both left-handed and right-handed leptons and quarks, it generates effective 4-Fermi operators of the form $\bar{u}_R d_L \bar{e}_R \nu_L$. These lead, for example, to helicity-unsuppressed $\pi \to e\nu$ decays, which are severely constrained by experiment [7, 18]. This eliminates the possibility of mixing $\Phi_{eQ}$ with any leptoquark that would lead to a CC signal, since by definition such a state has to couple to the left-handed lepton doublet containing a $\nu$. Similarly, option (ii) is not realized, given that the only other $Q = 5/3$ state is in $\Phi^*_{eQ}$. Thus we are left with only option (i).

The $Q = 2/3$ component of $\Phi_{Ld}$ can only mix with either the $Q = 2/3$ component of $\Phi_{Lu}$, or with the $Q = 2/3$ component of the triplet $\Phi^*_{LQ}$. Such mixings can arise from terms in the Lagrangian,

$$\mathcal{L} \supset \lambda \Phi^*_{Lu} \Phi_{Ld} H^2 + \tilde{\mu} \Phi_{Ld} \Phi_{LQ} H^*,$$

where $H$ is the SM Higgs doublet. In a supersymmetric context, we can identify $H^* = H_d$ and $H = H_u$. The second term arises generically in a softly-broken supersymmetric model, for instance from $A$-terms. The first term seems to require additional fields.

1More specifically, we are excluding scattering off of $\bar{u}$ or $\bar{d}$ quarks. We are not considering the possibility of scattering off of $s$ or $c$ sea quarks [10, 12, 13], where the required Yukawa couplings must be of $O(1)$. 

3
In Eq. (1) the first term is $B$ and $L$ conserving, while the second term violates $L$ (but not $B$) by $\Delta L = 2$. Thus the second term can lead to lepton number violating processes such as $\pi^+ \rightarrow e^+ \nu_e$, which is not helicity-suppressed. The constraints on the $\Delta L = 0$ process $\pi^+ \rightarrow e^+ \nu_e$ also apply here, requiring either leptoquark masses over several TeV or Yukawa couplings of $\Phi_{LQ}$ too small to be of use for producing a CC interaction at HERA. Thus we will not consider this possibility any further.

This leaves us with only the possibility of $(\Phi_{Ld}, \Phi_{Lu})$ mixing. In principle both the light and heavy mass eigenstate admixtures of the $Q = 2/3$ leptoquark states could be currently produced by HERA. This is because both have couplings to $e^+ d$ after mixing, and it is possible that they have comparable masses. It is also possible to produce the $\phi_{Lu}^{5/3}$ state at HERA which leads to no CC signal on its own. (We will return to the constraints on such a scenario arising from CDF/D0 later.) We think this is an interesting possibility, but we will focus our discussion on the simpler possibility that only the lighter mixed eigenstate is being produced at HERA; all the other states are assumed to be heavy. We denote this light mixed state as $\phi_1^{2/3} = \cos \theta \phi_{Ld}^{2/3} + \sin \theta \phi_{Lu}^{2/3}$, and the heavier mixed state (the orthogonal combination) as $\phi_2^{2/3}$. The initial leptoquark Yukawa couplings before mixing are

$$\mathcal{L} = \lambda_1 Ld \Phi_{Ld} + \lambda_2 Lu \Phi_{Lu} + h.c. \quad (2)$$

This leads to couplings of the light $\phi_1$ state of $(\lambda_1 \cos \theta d + \lambda_2 \sin \theta \nu_u)\phi_1^{2/3}$, and an associated CC branching ratio

$$\text{Br}_{\nu_j}(\phi_1^{2/3} \rightarrow \nu u) = \frac{\lambda_2^2 \sin^2 \theta}{\lambda_1^2 \cos^2 \theta + \lambda_2^2 \sin^2 \theta} \quad (3)$$

For $\lambda_2 \sin \theta \sim \lambda_1 \cos \theta$ this results in comparable CC and NC signals at HERA. Note that to maintain the overall NC event rate, the effective coupling $\lambda_1 \cos \theta$ (which was $\simeq 0.04$ in the absence of mixing) has to be increased by a factor of $1/\sqrt{1 - \text{Br}_{\nu_j}}$.

It should be noted that CDF has recently announced a lower limit of 210 GeV (at 95% C.L.) on scalar leptoquarks that decay into electrons and quarks with branching ratio 1, using the NLO QCD calculations of Ref. [17]. (The limits on a leptoquark decaying to a quark and a neutrino are much weaker.) This is starting to significantly constrain the (unmixed) leptoquark explanation of the HERA NC data. (From the calculations of Ref. [19], it can be seen that this translates into a limit on vector leptoquarks that essentially excludes this option for explaining the HERA NC anomaly.)

In the mixed scalar leptoquark scenario the situation is significantly changed, since the branching ratio to electrons and jets ($\text{Br}_{ej} = 1 - \text{Br}_{\nu_j}$) is less than one. For example, if the branching ratio is 1/2, we estimate the mass limit on $\phi_1^{2/3}$ to be somewhat below 190 GeV, which is perfectly compatible with the HERA data. In this case, however, the heavier $\phi_2^{2/3}$ also decays into $e^+ + \text{jets}$ with a branching ratio

\footnote{This includes the enhancement coming from NLO QCD effects [12, 20].}
of 1/2, so it contributes to any possible signal at CDF/D0. Setting the mass of \( \phi_{1}^{2/3} \) at 200 GeV, we estimate that the mass of \( \phi_{2}^{2/3} \) must be \( \gtrsim 225 \) GeV (for \( \text{Br}_{ej} = 1/2 \)) using the analysis of [17].

One consequence of the CDF/D0 data is that it strongly disfavors \( \Phi_{eQ} \) as a possible explanation of the HERA NC anomaly. As we argued above, it is not possible to substantially mix this state with any other which has couplings to neutrinos. Thus both components of \( \Phi_{eQ} \) always decay into electrons + jets. Furthermore, since \( \Phi_{eQ} \) is an unmixed doublet the \( \rho \)-parameter constraint does not allow the mass of the heavier component to be arbitrarily large. Typically, one finds that the heavier mass is constrained to be below 250 GeV, given that the lighter mass is fixed at \( \simeq 200 \) GeV. Furthermore, there is a perturbativity constraint on the splitting since it is entirely due to electroweak symmetry breaking: \( \delta m^2 \sim \lambda v^2 \lesssim (250 \text{ GeV})^2 \) for \( \lambda \lesssim 1 \). Therefore CDF/D0 would see two states each decaying to electrons with branching ratio one. For instance a heavy state at 250 GeV contributes 0.03 pb to the CDF cross section, which implies that the lighter state must be above 220 GeV at 95\% C.L. Alternatively the quoted CDF limit for a single state implies a limit on a degenerate doublet of \( M_{\Phi} > 234 \) GeV at 95\% C.L., probably beyond the interesting mass range for HERA.

2.1 The \( \rho \)-parameter

It is natural to consider the implications of the \( \rho \)-parameter constraints on scenarios in which scalar leptoquark multiplets mix. We have investigated this in detail following Ref. [21]. In particular \( \Delta \rho = (\Pi_{+-} - \Pi_{33})/m_{W}^2 \) where the indices label SU(2) weak-isospin, and the general expression for the quantities \( \Pi_{ab} \) is given by

\[
\Pi_{ab} = \frac{g^2 C}{2} \int \frac{d^4 k_E}{(2\pi)^4} k_E^2 \text{Tr}([T_a, \Delta(k)][T_b, \Delta(k)]). \tag{4}
\]

In this equation the \( T \)'s are SU(2) matrices in the (reducible) representation of the scalar multiplets, \( \Delta(k) = 1/(k_E^2 + M^2) \), with \( M^2 \) the mass squared matrix, \( g \) is the weak coupling, and \( C \) is a possible color factor (\( C = 3 \) for scalar leptoquarks).

The resulting analytic expressions for \( \Delta \rho \) in the presence of mixing between two SU(2) representations are quite complicated. However, in the case where two weak doublet leptoquarks (such as \( \Phi_{Ld} \) and \( \Phi_{Lu} \)) are mixed in such a way that three of the four resulting leptoquarks are degenerate, the expressions simplify greatly. In this special case

\[
\Delta \rho = \frac{3G_F \cos^2 2\theta}{8\sqrt{2}\pi^2} \left[ m_{1}^2 + m_{2}^2 + \frac{2m_{1}^2 m_{2}^2}{m_{1}^2 - m_{2}^2} \ln \left( \frac{m_{1}^2}{m_{2}^2} \right) \right], \tag{5}
\]

and it is clear then that for maximal mixing (\( \theta = \pi/4 \)), \( \Delta \rho \) vanishes. For the general case we have investigated the contribution of Eq. (4) to \( \Delta \rho \) numerically. In many cases it is possible to find substantial negative contributions to \( \rho \). For example, if we take the mass eigenvalues to be (202, 273, 240, 240) GeV, with maximal mixing
between the first two (the \( Q = 2/3 \) states), then we find \( \Delta \rho = -0.001 \). It is possible to find negative values of greater magnitude (especially for large mixing), as well as small positive values, if one allows the mass spectrum to vary consistent with the CDF/D0 limits. Thus the \( \rho \)-parameter provides no significant constraint on the mass spectrum in the \((\Phi_{Ld}, \Phi_{Lu})\) mixed case. (Note that if we require substantial mixing and one eigenvalue fixed around 200 GeV, then perturbativity does not allow any of the other states to become arbitrarily massive.)

### 2.2 Atomic parity violation

The mixing scenarios also have consequences for the atomic parity violation (APV) experiments. In the presence of scalar leptoquarks the predicted weak charge of a nucleus shifts by

\[
\Delta Q_{W}^{\text{LQ}} = -2 \left( \frac{\lambda_{LQ}/M_{LQ}}{g_{W}/M_{W}} \right)^{2} (\delta Z + \delta N, N).
\]

For the leptoquarks of interest, the values of \((\delta Z, \delta N)\) are: \((2,1)\) for \( \Phi_{Lu} \) and \((1,2)\) for \( \Phi_{Ld} \).

Recently the measurement of the weak charge \( Q_{W} \) of Cesium \((Z = 55, N = 78)\) has significantly improved \[22\], leading to a new value \( Q_{W}^{\text{exp}}(\text{Cs}) = -72.11 \pm 0.93 \). This is to be compared to the SM prediction of \( Q_{W}^{\text{SM}}(\text{Cs}) = -73.20 \pm 0.09 \). There are also reasonably good measurements for Thallium \((Z = 81, N = 205)\), leading to \( Q_{W}^{\text{exp}}(\text{Th}) = -115.0 \pm 4.5 \) compared to the prediction \( Q_{W}^{\text{SM}}(\text{Th}) = -116.8 \pm 0.19 \[23\].

For the central values of the masses and couplings of the \( \Phi_{Lu} \) and \( \Phi_{Ld} \) states found in a fit to the NC HERA data \((\lambda_{Lu} \simeq 0.020, \lambda_{Ld} \simeq 0.04, \text{with masses } \simeq 200 \text{ GeV in both cases})\), \( Q_{W}(\text{Cs}) \) shifts by the small amounts \( \Delta Q_{W}(\text{Cs}) = -0.09 \) and \( \Delta Q_{W}(\text{Cs}) = -0.40 \), respectively, further away from experiment.

In the presence of mixing, the expression for \( \Delta Q_{W} \) changes to

\[
\Delta Q_{W} = -2 \left( \frac{\delta Z + \delta N, N}{(g_{W}/M_{W})^{2}} \right) \left[ \left( \frac{\lambda_{1} \cos \theta}{m_{1}} \right)^{2} + \left( \frac{\lambda_{1} \sin \theta}{m_{2}} \right)^{2} \right] + \cdots
\]

The ellipsis denotes the contributions from the unmixed components of the heavier multiplet, which depend upon its unknown Yukawa coupling \( \lambda_{2} \) to SM fermions. Since in the \((\Phi_{Ld}, \Phi_{Lu})\) mixing case the combination \( \lambda_{1} \cos \theta \) is now fixed to be \( \simeq 0.04 \) by the magnitude of the NC excess, it is clear that the \( (\lambda_{1} \sin \theta/m_{2})^{2} \) term increases the shift in \( \Delta Q_{W} \) compared to the unmixed case. For instance, in the case of maximal mixing one finds roughly a doubling of \( \Delta Q_{W} \), relative to the unmixed case. (This shift is only increased by the terms proportional to \( \lambda_{2}^{2} \) omitted in Eqn. (6).) For Thallium, all the shifts are about twice as large, but because of the much larger experimental error this corresponds to a statistically less significant change.

Thus, overall, the discrepancy between the APV measurements and the SM tends to increase in the case of significant \((\Phi_{Ld}, \Phi_{Lu})\) mixing, by approximately 0.75\( \sigma \) for Ce-
sium (the exact value depending on the mass \( m_2 \), the mixing angle, and the unknown Yukawa coupling \( \lambda_2 \)).

### 2.3 Heavy leptoquark decays

We have seen from the discussions above that the leptoquark interpretation of the HERA NC data allows a comparably large cross section in the charged current mode as well, provided that the leptoquark produced is an admixture of different leptoquark states. The masses of these additional leptoquarks are constrained by the \( \rho \)-parameter, and perturbativity, to be roughly below 300 GeV. It is then of interest to ask how these extra leptoquarks could be detected once they are produced at colliders. Here we wish to point out some interesting decay channels of these heavier leptoquarks which will be of relevance for their search at the Tevatron.

For \((\Phi_{Ld}, \Phi_{Lu})\) leptoquark mixing, since both are doublets, there are four physical states. The \( \phi_{Ld}^{2/3} \) mixes with the \( \phi_{Lu}^{2/3} \) forming two mass eigenstates \((\phi_{1}^{2/3} \text{ and } \phi_{2}^{2/3})\) of masses \( m_1 \) and \( m_2 \), with \( m_1 \approx 200 \text{ GeV} \). The two other states \( \phi_{Ld}^{-1/3} \) and \( \phi_{Lu}^{5/3} \) are unmixed, and we denote their masses by \( m_3 \) and \( m_4 \). The two body decay \( \phi_{Ld}^{-1/3} \rightarrow d + \bar{\tau} \) is always open, but the width for this decay is suppressed by a small Yukawa coupling squared \( \lambda^2 \sim (0.04)^2 \). If \( m_3 \) is larger than \( m_1 + m_W \), the decay \( \phi_{Ld}^{-1/3} \rightarrow \phi_{1}^{2/3} + W \) will be open and will be dominant. One signature will be \( 3j + e; \) a more spectacular signature into \( \ell \nu e j \) occurs about 1/3 as often. If this channel is closed, there is still the three-body decay through a virtual \( W \) which can compete with the \( d + \bar{\tau} \) decay rate. When the \( W \) is off-shell, the rate for the three-body decay is given by

\[
\Gamma(\phi_{Ld}^{-1/3} \rightarrow \phi_{1}^{2/3} f \bar{f}) = \frac{A_f^2 A_f^2}{384 \pi^3 m_3} \int_0^{1-\sqrt{t}} dt \frac{(r^2 + (1-t)^2 - 2r(1+t))^{3/2}}{(t-s)^2}
\]

where \( r \equiv m_1^2/m_3^2, \ s \equiv m_W^2/m_3^2, \ A_s = A_f = g/\sqrt{2} \), and summation of different helicities is assumed. The competing decay has a rate

\[
\Gamma(\phi_{Ld}^{-1/3} \rightarrow d + \bar{\tau}) = \frac{\lambda^2}{16\pi} m_3.
\]

Taking \( m_1 = 200 \text{ GeV} \), the total width for the three body decay is found to be \((0.73 \text{ MeV}, 2.0 \text{ MeV}, 5.3 \text{ MeV}) \) for \( m_3 = (250, 260, 270) \text{ GeV} \). These numbers are to be compared with the two-body decay width \( \Gamma \approx 7 \text{ MeV} \) for \( \lambda = 0.04 \). Identical results hold for the decay of the \( \phi_{Lu}^{5/3} \) leptoquark.

What about the heavier \( \phi_{2}^{2/3} \) leptoquark? Since the mass eigenstates are combinations of \( Q = 2/3 \) states carrying different \( T_3 \), there is a residual off-diagonal \( \phi_{2}^{2/3} \phi_{2}^{2/3} Z \) coupling with a coefficient \( g \sin 2\theta/(2 \cos \theta_W) \), where \( \theta \) is the leptoquark mixing angle. This leads to the three body decay \( \phi_{2}^{2/3} \rightarrow \phi_{1}^{2/3} + Z^* \rightarrow \phi_{1}^{2/3} + f + \bar{\tau} \). The rate is given by Eq. (1), now with \( A_s = g \sin 2\theta/(2 \cos \theta_W) \), \( A_f = g(T_3 - Q \sin^2 \theta_W)/\cos \theta_W \),
\( r = m_2^2/m_3^2 \) and \( s = m_3^2/m_3^2 \). Again, this mode can compete with the 2-body decay mode. For instance, if \( m_2 = (260, 270, 280) \) GeV with maximal mixing then the total width for the 3-body decay is \((0.7, 1.8, 4.1) \) MeV. If enough of the heavier leptoquarks can be produced, the gold-plated signature will be \( \ell^+ \ell^- e^+ e^- jj \). Here the \( \ell^+ \ell^- \) come from the decay of \( \phi_2 \) to \( Z^* \phi_1 \) with the \( \phi_1 \) then further decaying to \( ej \); the second \( \phi_2 \) on the other hand decays directly to \( ej \).

3 Conclusions

In the presence of mixing between different scalar leptoquark SU(2) multiplets we have demonstrated that it is possible to simultaneously account for the HERA high-\( Q^2 \) NC anomaly, and produce a CC anomaly of comparable magnitude. The branching ratio to electrons and jet(s) of the lightest leptoquark state that by assumption is being produced at HERA is consequently reduced. This results in a significant weakening of the recently announced CDF/D0 limits on scalar leptoquarks, and masses consistent with an explanation of HERA are comfortably within the allowed range.

However we showed that there is only one possibility for such a successful mixed leptoquark scenario: the \( \Phi_{Ld} \) doublet leptoquark multiplet must mix with the \( \Phi_{Lu} \) doublet. We investigated various aspects of the associated phenomenology. In particular, this scenario often allows relatively large splittings among the leptoquarks while satisfying the \( \rho \)-parameter constraints. Indeed it is possible to find substantial negative contributions to \( \rho \) in the case of large mixing. We also point out that there are novel possibilities for the decays of heavier members of the leptoquark multiplets, which might be relevant for searches at the Tevatron.

Finally, it should be emphasized that the mixed scenario does not address what is in our opinion the most serious problem facing leptoquark (or \( R \)-parity violating squark) explanations of the HERA anomaly, namely, the very serious flavor problem that all such models engender \[5, 6, 7\].

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