Comments on the high-$Q^2$ HERA anomaly

K.S. Babu, Christopher Kolda, John March-Russell
and
Frank Wilczek

School of Natural Sciences,
Institute for Advanced Study,
Princeton, NJ, USA 08540

Abstract

Taking the reported high-$Q^2$ anomaly at HERA as a signal of new physics, we show that several independent considerations point towards $s$-channel leptoquark production as the most attractive interpretation. We argue that even this option is highly constrained by flavor-changing processes: the couplings must be accurately diagonal in the quark and lepton mass eigenstate basis and should preserve individual quark and lepton family numbers. We propose a dynamical mechanism that might produce this pattern; it has distinctive experimental consequences.

\[1\] Research supported in part by DOE grant DE-FG02-90ER40542, and by the W. M. Keck Foundation. Email: babu@sns.ias.edu, kolda@sns.ias.edu, jmr@sns.ias.edu, wilczek@sns.ias.edu
Recently, the H1 \cite{1} and ZEUS \cite{2} collaborations, which have been studying $e^+p$ collisions on the HERA ring since 1993, announced an anomaly in high-$Q^2$ $e^+p$ collisions. Using a combined accumulated luminosity of $34.3\,\text{pb}^{-1}$ in $e^+p \rightarrow eX$ mode at $\sqrt{s} = 300\,\text{GeV}$, the two experiments have observed 24 events with $Q^2 > 15000\,\text{GeV}^2$ against a Standard Model (SM) expectation of $13.4 \pm 1.0$, and 6 events with $Q^2 > 25000\,\text{GeV}^2$ against an expectation of only $1.52 \pm 0.18$. If we take these reports at face value, there seems to be little possibility of explaining the anomaly within the Standard Model. In particular, the high-$Q^2$ events are clustered at Bjorken-$x$ values near 0.4 to 0.5; the quark distribution functions at such large $x$ are well-measured at lower $Q^2$, and QCD allows for a very precise scaling to the observed $Q^2$. (By contrast, the superficially similar reported anomaly in the high-$E_T$ dijet cross-section at FNAL \cite{3} can plausibly be ascribed to uncertainties in the gluon distribution functions.) The peaked distribution of these high-$Q^2$ events in $x$ is also notable. If the new physics is assumed to be an $s$-channel resonance, this distribution translates into a mass determination. 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 $M_{2\alpha} = 202 \pm 14\,\text{GeV}$ and $M_e = 199 \pm 8\,\text{GeV}$ respectively. Similarly, for the five events selected by ZEUS, $M_{2\alpha} = 231 \pm 16\,\text{GeV}$ and $M_e = 219 \pm 12\,\text{GeV}$.

HERA is capable of running in two modes: $e^-p$ and $e^+p$. In the former mode H1 and ZEUS have accumulated $1.53\,\text{pb}^{-1}$ 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 $p_T$. The anomaly discussed above is in the neutral current (NC) reaction $e^+p \rightarrow eX$ channel. H1 has also announced its findings in the $e^+p \rightarrow \nu X$ charged current (CC) channel. They find 3 events at $Q^2 > 20000\,\text{GeV}^2$ with an expectation of $0.74 \pm 0.39$, but no events with $Q^2 > 25000\,\text{GeV}^2$. ZEUS has not announced its CC data. Compared to the NC channel, the CC signal is considerably less statistically significant, and we therefore regard the question of whether new physics in this channel is required as open.

Both detectors at HERA are highly efficient at tagging muons. Apart from one such event in the 1994 H1 data \cite{4} (which occurs in a very different kinematic region from the events under consideration here), neither experiment has evidence for final state muons.

Reprising: H1 and ZEUS see an excess of high-$Q^2$ NC events in $34.3\,\text{pb}^{-1}$ of $e^+p$ data, with no corresponding anomaly in $1.53\,\text{pb}^{-1}$ of $e^-p$ data. There is no clear evidence for or against a similar anomaly in the CC mode. There is no signal for final state $\mu$'s. There is evidence that the events seen are peaked at $x \sim 0.45-0.55$, but there is some disagreement between the two experiments concerning the central $x$ value at the peak. If the signal is real, and not a statistical fluctuation, there appears to be no way to change the parameters of the SM to explain it. Let us entertain the hypothesis that this data represents a genuine signal, and investigate
the consequences.

**New Physics.** What kind of new physics could be responsible for the HERA anomaly? We consider only physics that can be described by an $SU(3) \times SU(2) \times U(1)$-invariant effective Lagrangian using perturbation theory.

There are 3 kinematic channels through which the $ep$ scattering might be occurring: in the $s$-channel through a resonance with non-zero lepton and baryon numbers (a “leptoquark”), in the $u$-channel again via a leptoquark, or in the $t$-channel via a particle without lepton or baryon number (this includes Higgs or $Z'$ exchange or contact interactions). We will discuss the $t$ and $u$-channels first.

If the intermediate state is a $t$-channel scalar or vector, then there are two kinematic limits in which very different constraints play a role. For a light $Z'$ (the results hold equally well for a scalar with a suitably rescaled coupling), the CDF and D0 experiments provide strong bounds from searches for $\overline{q}q \rightarrow Z' \rightarrow e^+e^-, \mu^+\mu^-$. Assuming significant branching ratios of the $Z'$ to leptons, they rule out $Z'$ masses below about 650 GeV. For masses greater than this bound, the $Z'$ can be integrated out and one can work in terms of effective 4-fermion contact interactions. By convention, one writes the operators:

$$L = \sum_{i,j=L,R} \frac{4\pi}{(\Lambda_{ij}^q)^2} \eta_{ij}^q (\bar{e}_i \gamma_\mu e_i) (\bar{q}_j \gamma^\mu q_j)$$

where $q = u, d$ and $\eta_{ij}^q = \pm 1$. Thus there are 8 different contact interactions, times 2 signs of $\eta$.

To analyze how well each operator fits the observed data at HERA, we perform a standard $\chi^2$ analysis with one free parameter, namely $\Lambda_{ij}^q$. For the fit, we use the combined bin-by-bin data of ZEUS and H1 for bins starting at $Q^2=(10000, 15000, 20000, 25000, 30000, 35000)$ GeV$^2$ respectively, with each bin (except the last) being 5000 GeV$^2$ wide; the last bin goes from $Q^2 = 35000$ GeV$^2$ to $Q^2 = s = 90000$ GeV$^2$. Bin by bin, ZEUS and H1 combined see (29, 14, 4, 2, 2, and 2) events.

For each operator and each choice of $\Lambda_{ij}^q$ we calculated the number of events expected in each $Q^2$ bin at HERA. H1 and ZEUS claim efficiencies approaching 80% in the $Q^2$ region of interest, and our own calculations of the SM and new physics cross-sections were scaled appropriately. For the parton-level calculation, we generalized the results of Ref. to contact interactions. The parton-level calculations were then folded into the CTEQ3M parton distribution functions to get the physical event rates.

The Standard Model, with 6 degrees of freedom has a $\chi^2/dof=4.0$, which is disfavored at greater than 99.9% C.L. For the contact terms, we demand a fit better than $2\sigma$ (95% C.L.) to the data, which for $6 - 1 = 5$ degrees of freedom, translates to $\chi^2/dof < 2.2$. For each operator, we find upper bounds on $\Lambda_{ij}^q$ as given in Table. OPAL has recently announced 95% C.L. lower bounds on the scales $\Lambda$ of each

\[1\] Thus our remarks do not apply to proposals such as that of Ref. 6.
where $C_{1q} = \frac{\sqrt{2\pi}}{G_F} \left( \frac{\eta_{RL}^q}{(\Lambda_{RL}^q)^2} - \frac{\eta_{LL}^q}{(\Lambda_{LL}^q)^2} - \frac{\eta_{LR}^q}{(\Lambda_{LR}^q)^2} + \frac{\eta_{RR}^q}{(\Lambda_{RR}^q)^2} \right)$. (3)

For any one operator with $\Lambda \lesssim 3$ TeV, $\Delta Q_W \approx \pm 20$, which is decisively excluded by the APV experiments. Logically, we cannot exclude the possibility of a conspiracy, with cancellations among individually large contributions from several operators (this can be natural however for contact interactions generated by a parity-conserving gauge interaction), but clearly these contact terms provide at best a marginally consistent parameterization for understanding the HERA data.

A $u$-channel leptoquark $\Phi$, in the heavy mass limit, goes over into the same types of contact interactions just discussed. But in this case an additional problem for light leptoquarks presents itself within the HERA data. Given $e^+p$ scattering in the $u$-channel with a valence (or sea) quark, by crossing and charge-conjugating the Feynman diagram, one arrives at $e^-p$ scattering in the $s$-channel off the same valence (or sea) quark. Therefore $\sigma(e^-p) \simeq (M_\Phi/\Gamma_\Phi)\sigma(e^+p)$ due to resonant production of $\Phi$ in $e^-p$ scattering, where $\Gamma_\Phi$ is the leptoquark width:

$$\Gamma_{\text{scalar LQ}} = n \frac{\lambda^2}{16\pi} M_{LQ}, \quad \Gamma_{\text{vector LQ}} = n \frac{\lambda^2}{24\pi} M_{LQ},$$ (4)

where $n$ is the number of available leptoquark decay channels. Given typical values $\Gamma_\Phi \sim 10$ MeV, then even with its much smaller integrated luminosity, this represents
Table 2: List of scalar leptoquark operators. For each operator, the $SU(3) \times SU(2) \times U(1)_{Y}$ 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 $\bar{e}, \bar{u}$ and $\bar{d}$ are $SU(2)$ singlets.

| Operator | SU(3) | SU(2) | U(1) | CC | mode |
|----------|-------|-------|------|----|------|
| $L_i Q_j \Phi e^{ij}$ | $3$ | $1$ | $1/3$ | Yes | $e^-$ |
| $L_i Q_j \Phi e^{ij}$ | $3$ | $3$ | $1/3$ | Yes | $e^-$ |
| $L_i \bar{u} \Phi e^{ij}$ | $3$ | $2$ | $7/6$ | No | $e^+$ |
| $L_i \bar{d} \Phi e^{ij}$ | $3$ | $2$ | $1/6$ | No | $e^+$ |
| $\bar{e} Q_i \Phi e^{ij}$ | $3$ | $1$ | $-1/3$ | No | $e^-$ |
| $\bar{e} \bar{u} \Phi$ | $3$ | $1$ | $-4/3$ | No | $e^-$ |

Thus $s$-channel production is the most attractive option. It is, moreover, consistent with the peaked distribution in $x$ observed at HERA. In this channel an important question arises, whether the $e^+ p$ scattering is off valence or sea quarks. If the scattering were off sea quarks, then by charge-conjugating the relevant diagram, one would arrive at $e^- p$ scattering off valence quarks, also resonant. At $x \approx 0.5$, the valence and sea parton distribution functions come in the approximate ratio $u_v \approx 4d_v \approx 200\bar{u}_s = 200\bar{d}_s$. (Recall that as $x \to 1$, $u_v(x) \approx 2d_v(x)/(1 - x)$.) So for every one anomalous event observed in the $e^+ p$ mode, H1 and ZEUS should have found between 2 to 9 such events in the $e^- p$ mode (depending on whether the coupling is to $u$ or $d$-quarks), despite the small integrated luminosity. Since no such excess has been observed, the $e^+ p$ anomaly must be described by $s$-channel production of a leptoquark coupling to valence quarks in the proton.

**Scalar Leptoquarks.** For scalar leptoquarks, there are only a few operators which are gauge-invariant, renormalizable and couple to both electrons and quarks. They are listed in Table 2. Also shown are the quantum numbers of the leptoquark, $\Phi$, under $SU(3) \times SU(2) \times U(1)_{Y}$. In the column “CC” is indicated whether or not the operator leads to CC events at HERA in addition to the NC. In the last column (“mode”) is listed the dominant production mode for the given leptoquark. We already argued that the events at HERA must be coming from $s$-channel scattering off of valence quarks in the proton; such operators are listed as “$e^+$” mode in the table. The remaining “$e^-$” operators would have been already detected in HERA’s $e^- p$ data given the size of coupling necessary to explain the anomaly in the $e^+ p$ data.

Note that if a leptoquark couples significantly to both LH and RH 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 $\pi \rightarrow e\nu$ decays, which are severely constrained by experiment \cite{14}. Among the operators relevant at HERA, this means that we may not identify $\Phi_{eQ} = \Phi_{Lu}^*$ (where the subscripts indicate the SM fermions to which the leptoquark couples) despite their identical quantum numbers. Alternatively, for a $\Phi(3,2,7/6)$ we must forbid one or the other of its $L\pi\Phi$ or $\tau\Phi^*$ couplings.

Of the 7 leptoquark operators listed in Table 2, only 3 are consistent with the HERA data as we interpret it: $\Phi_{Lu}$, $\Phi_{Ld}$ and $\Phi_{eQ}$. All three are $SU(2)$ doublets, and we will assume throughout the rest of this analysis that the member coupling to electrons is the lighter so that it does not decay to the component coupling to neutrinos and a real or virtual $W$. Such a decay would have a very different signature at HERA. We also note that the leptoquark which can appear in a $\mathbf{5}$ of $SU(5)$ is not among the three possible states useful for explaining the HERA data; however, the $\Phi_{Ld}$ leptoquark can fit into a $\mathbf{10}$ of $SU(5)$.

Notice that all scalar leptoquarks which would have given a CC signal have been ruled out already by lack of NC events in $e^-p$ mode. Thus for scalar leptoquarks, we conclude that there will be no CC signal at HERA. Conversely, if a CC signal is seen at HERA, a scalar leptoquark interpretation is strongly disfavored.

We performed a similar $\chi^2$ analysis here to the one described above for contact interactions, except there are now 2 independent variables: $M_{LQ}$ and $g_{LQ}$. Relevant cross-section calculations have been performed in Ref. \cite{11}. Here again the APV measurement can strongly constrain the range of parameters allowed. For scalar leptoquarks one finds

$$\Delta Q_{W}^{LQ} = -2 \left( \frac{g_{LQ}/M_{LQ}}{g_{W}/M_{W}} \right)^2 (\delta_Z Z + \delta_N N). \quad (5)$$

For the leptoquarks of interest, the values of $(\delta_Z, \delta_N)$ are: $(-2,-1)$ for $\Phi_{eQ}$, $(2,1)$ for $\Phi_{Lu}$, and $(1,2)$ for $\Phi_{Ld}$. For a given mass and coupling, the constraint on $\Phi_{eQ}$ will be weaker than for the others, since it shifts $Q_W$ in the direction of experiment.

Given the $6+1-2 = 5$ degrees of freedom, we explore the range of $(M_{LQ}, g_{LQ})$ which give $\chi^2/\text{dof} < 2.2$ (i.e., 95% C.L.). The 95% confidence regions are shown in Figure 1 for each of $\Phi_{eQ}$, $\Phi_{Lu}$, and $\Phi_{Ld}$. For $\Phi_{Lu}$ and $\Phi_{Ld}$, the leptoquark couplings are constrained to be small by the APV bounds discussed above. For $\Phi_{eQ}$, we assume that the members of the leptoquark doublet are nearly degenerate and both are produced at HERA; if one or the other is significantly heavier, then the best fit values as far as HERA is concerned go over to those of $\Phi_{Lu}$ or $\Phi_{Ld}$, as appropriate. It may seem that in the combined HERA + APV analysis for $\Phi_{eQ}$, large values of the corresponding coupling, $g_{LQ}$, still provide good fits since they improve agreement of theory with the APV data. However, as we discuss later, a combination of rare decay constraints coming from $K_L \rightarrow \pi^0 \ell^+\ell^-$ and $D^0 \rightarrow \pi^0 \ell^+\ell^-$ exclude values of $g_{LQ} > 0.08$ for this operator for masses in the interesting range.

We also calculate “1$\sigma$” bounds on $M_{LQ}$ and $g_{LQ}$ by demanding $\chi^2 \leq \chi^2_{\text{min}} + 1$. These bounds are not true 1$\sigma$ bounds since the iso-$\chi^2$ lines are far from elliptical but
Figure 1: 95% C.L. regions in the \((M_{LQ}, g_{LQ})\) plane derived from fitting to the HERA \(Q^2\) distribution and APV in cesium. The three scalar leptoquark operators are shown: \(\Phi_{Lu}\) (solid), \(\Phi_{eQ}\) (dotted), and \(\Phi_{Ld}\) (dashed). For \(\Phi_{Lu}\) and \(\Phi_{Ld}\) the best fit values for \(M_{LQ}\) and \(g_{LQ}\) are shown with 1\(\sigma\) error bars. For \(\Phi_{eQ}\), couplings above 0.08 are excluded by a combination of rare decay constraints.

we consider the bound indicative of where the best fit values fall. For the \(\Phi_{Lu}\) and \(\Phi_{Ld}\) leptoquarks, one finds:

\[
\Phi_{Lu}: M_{LQ} = (200 \pm 8) \text{ GeV}, \quad g_{LQ} = 0.025 \pm 0.005 \\
\Phi_{Ld}: M_{LQ} = (195^{+8}_{-3}) \text{ GeV}, \quad g_{LQ} = 0.05 \pm 0.005
\]  

A similar bound on the \(\Phi_{eQ}\) leptoquark is difficult to determine. The \(\chi^2\) is small over a wide range of masses \((190 \text{ GeV} < M_{LQ} \lesssim 260 \text{ GeV})\) and couplings \((0.01 < g_{LQ} \lesssim 0.08)\), and once again it is only the \(x\)-distribution at HERA which can further constrain them.

It is noteworthy that the fits have no information put into them \textit{a priori} about the observed distributions in \(x\). Nevertheless, for the \(\Phi_{Lu}\) and \(\Phi_{Ld}\) leptoquarks, the best fit values to the shape of the \(Q^2\) distribution are at \(M_{LQ}\) consistent with the \(M_{LQ} = \sqrt{xs}\) extracted from the HERA data. We consider this an additional piece of evidence in favor of an \(s\)-channel interpretation of the HERA results.
Vector Leptoquarks. The HERA data, considered by itself, can be similarly well described by an s-channel exchange of a vector leptoquark with $M_{LQ} \approx 200 \text{ GeV}$ and coupling $\sqrt{2}$ smaller than its corresponding scalar leptoquark. However, such states are disfavored by an analysis of Run I data taken by the D0 collaboration at Fermilab, as we now argue. First, note that D0 has reported a bound on 1st generation scalar leptoquarks of 175 GeV at the 95% confidence level [12]. This corresponds to a bound on the leptoquark production cross-section (including the effect of cuts and efficiencies) of $\sigma \lesssim 0.4 \text{ pb}$ [13]. Now, the production cross-section for a pair of vector leptoquarks, $\Phi_\mu$, at the Tevatron has a model dependence that stems from the possibility of a coupling $\kappa \Phi_\mu^\dagger G^{\mu\nu} \Phi_\nu$ to the gluon field strength tensor $G^{\mu\nu}$. (There is an insignificant contribution to the production cross section from the leptoquark Yukawa couplings given the determination of their size from the HERA data.) It can be seen from the analysis of Hewett, et al [14] that the contribution from $\kappa$ destructively interferes most strongly with the process $q\bar{q} \rightarrow g \rightarrow \Phi^\dagger \Phi$ at values $\kappa \approx -0.5$. For this most conservative value, the production cross-section for pairs of vector leptoquarks at the Tevatron exceeds 0.4 pb for masses $M_{LQ} < 215 \text{ GeV}$ [15]. Thus such masses are excluded at the 95% confidence level. If on the other hand we take the value of $\kappa$ to lie in the range (0.0–1.0), then masses $M_{LQ} \lesssim 240 \text{ GeV}$ are excluded. We therefore view vector leptoquarks as only a marginally consistent possibility at best.

Flavor Violation. The three effective interactions of scalar leptoquarks that we have identified as capable of explaining the HERA data are

$$\mathcal{O} = \lambda_{ij} L_i \Phi d_j^c = \lambda_{ij} (\nu_i d_j^c \phi^{-1/3} - e_i d_j^c \phi^{2/3})$$

$$\mathcal{O}' = \lambda'_{ij} L_i \Phi' u_j^c = \lambda'_{ij} (\nu_i u_j^c \phi^{2/3} - e_i u_j^c \phi^{5/3})$$

$$\mathcal{O}'' = \lambda''_{ij} Q_i e_j^c \Phi'' = \lambda''_{ij} (u_i e_j^c \phi^{-5/3} - V_{ik} d_k e_j^c \phi^{-2/3}) .$$

(Lowercase $\phi^O$'s correspond to the components of the leptoquark $SU(2)$ doublets of electric charge $Q$.) Here the operators are written in the mass eigenbasis, where $i, j$ are the generation indices and $V$ in $\mathcal{O}''$ is the CKM matrix. The flavor structure of these Yukawa matrices ($\lambda, \lambda', \lambda''$) is severely constrained by limits from rare processes (for earlier work in this regard, see [14]).

To be definite take the operator $\mathcal{O}$ first. If $\mathcal{O}$ explains the HERA data, $\lambda_{11} \approx 0.05$ is needed. The other elements of $\lambda$ are then constrained as follows. The decay $K_L \rightarrow e^+ e^-$ occurs at tree-level by the exchange of the $\phi^{2/3}$ leptoquark. However, the rate is strongly suppressed by a helicity factor $(m_e^2 / m_K^2)$ and therefore does not give any useful limit. On the other hand, the decay $K_L \rightarrow \pi^0 e^+ e^-$, which arises from the same tree-level quark diagram, is helicity unsuppressed. The limit on this decay, $Br(K_L \rightarrow \pi^0 e^+ e^-) \leq 4.3 \times 10^{-9}$, translates into a bound of $\lambda_{11} \lambda_{12} \leq 1.5 \times 10^{-4} (M_{\phi^{2/3}}/200 \text{ GeV})^2$. For $\lambda_{11} \approx 0.05$, this means $\lambda_{12} \leq 3 \times 10^{-3}$. Such a hierarchy pattern seems quite unusual; it deviates considerably from the pattern of Yukawa couplings that we have become used to in the quark sector.
The doublet partner $\phi^{-1/3}$ of $\phi^{2/3}$ must be nearly degenerate with it, else their mass–splitting will contribute to the $\rho$–parameter excessively. The tree–level exchange of $\phi^{-1/3}$ causes the decay $K^+ \to \pi^+ \nu\bar{\nu}$. The experimental limit $Br(K^+ \to \pi^+ \nu\bar{\nu}) \leq 2.4 \times 10^{-9}$ leads to the bound $\lambda_{11}\lambda_{22} < 1.2 \times 10^{-4}(M_{\phi}/200\text{ GeV})^2$. One again sees a severe limit on the second generation couplings.

The leptoquarks $\phi^{2/3}$ and $\phi^{-1/3}$ mediate the process $\mu \to e + \gamma$ through one loop induced magnetic moment interactions. The present limit on the branching ratio, $Br(\mu \to e + \gamma) < 4.9 \times 10^{-11}$, implies that $\lambda_{11}\lambda_{21} < 1.6 \times 10^{-4}(M_{\Phi}/200\text{ GeV})^2$. Similarly, the decay $K_L \to \mu e$ can occur at tree level if both $\lambda_{11}$ and $\lambda_{22}$ are nonzero. The limit on this decay, $Br(K_L \to \mu e) < 3.3 \times 10^{-11}$, translates into a bound of $\lambda_{11}\lambda_{22} < 2.8 \times 10^{-6}(M_{\Phi}/200\text{ GeV})^2$. Evidently it is not enough that the couplings are flavor diagonal; individual quark and lepton number must be preserved.

There are analogous constraints on the coupling $\lambda_{ij}$ of $\mathcal{O}'$ coming from $D^0 \to \pi^0 e^+ e^-$, etc, but they are weaker numerically, by about a factor of 5, in the Yukawa couplings. The couplings $\lambda_{ij}''$ in $\mathcal{O}''$ have the interesting feature that one cannot simultaneously suppress $D^0 \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 e^+ e^-$. Suppressing the more strongly constrained mode $K_L \to \pi^0 e^+ e^-$ leads to a limit on the individual diagonal Yukawa coupling $|\lambda_{11}'|^2 < 4 \times 10^{-3}(M_{\Phi'}/200\text{ GeV})^2$ from $D^0 \to \pi^0 e^+ e^-$. This is the bound imposed on the HERA + APV fit in Figure 4 for the $\Phi_{eQ}$ operator. There is also a stringent limit on the product $(\lambda'^T V)_{11}(\lambda'^T V)_{12}^*$ from $K_L \to \pi^0 e^+ e^-$ decay. In particular, if only $\lambda_{11}'$ is nonzero (in this basis), the constraint $|\lambda_{11}'|^2 < 6.8 \times 10^{-4}(M_{\Phi'}/200\text{ GeV})^2$, will nearly exclude the possibility of explaining the HERA data with this operator.

Additional constraints arise from box diagrams which induce $K^0 - \overline{K}^0$ mixing, $D^0 - \overline{D}^0$ mixing, etc, but these are less severe than the ones quoted above, essentially because they scale as $\lambda^4$ in the amplitude. One process worth noting is the box diagram contribution to $K_L \to \pi^0 \ell^+ \ell^-$ and $D^0 \to \pi^0 \ell^+ \ell^-$ with the exchange of one $W^\pm$ and one leptoquark. Such a diagram directly constrains the diagonal leptoquark coupling, although the limits are rather weak: $|\lambda_{22}|^2 \leq 0.06(M_{\Phi}/200\text{ GeV})^2$ from $K_L \to \mu^+ \mu^-$. 

\textit{Conclusion: A Model.} Limits arising from flavor physics provide very severe constraints on any model containing leptoquark degrees of freedom capable of explaining the HERA data. In the absence of a general principle, it strains credulity to postulate the required large number of tiny parameters in a fundamental theory. An adequate interpretation of the HERA data must address this question. Neither the direct introduction of fundamental leptoquark degrees of freedom, nor other possibilities such as $R$-parity violating couplings of MSSM squarks [10], naturally explains this remarkable flavor structure; namely that the leptoquarks must, to a very high degree of accuracy, couple diagonally to the mass-eigenstate quarks and leptons, and conserve individual quark and lepton numbers. Clearly what is required is that the underlying physics responsible for the HERA anomaly is universal in character with
regard to the generations.

The natural implementation of this universality is a gauge principle, with the three generations having identical charge assignments. We have seen that the HERA phenomenology disfavors $t$-channel $Z'$ exchange as an explanation compared to the production of an $s$-channel resonance. We are therefore led to consider the possibility that a new strong short-ranged gauge interaction leads to the formation of relatively light leptoquark quasi-bound states. Moreover, if the unification of couplings observed in the MSSM is to have any chance of being maintained, this gauge interaction must commute with the Standard Model interactions. As an example consider an additional $U(1)$ interaction at a strong coupling fixed point, spontaneously broken at the TeV scale. While one cannot reliably calculate the consequences of such an interaction, a not unreasonable hypothesis for the dynamics of such a theory might be that the low energy spectrum is saturated by resonances having small residual interactions. If the original gauge interaction commutes with $SU(5)$, then the resonances automatically fill out several complete $SU(5)$ multiplets, each having different flavor quantum numbers. More importantly, the generation independence of the $U(1)$ gauge coupling implies that the masses and couplings of the resonances (to free quarks and leptons) are to a good approximation invariant under an $SU(3)$ symmetry that rotates the generations. This symmetry is only broken by effects that depend on the usual Higgs Yukawa couplings, $h$, of the SM as $h^2$. The flavor physics limits discussed above are easily and naturally satisfied.

A model-independent prediction emerging from this scenario is the existence of a large multiplicity of very nearly degenerate resonances. This is to be expected from any model which preserves so carefully the $SU(3)$ flavor symmetries among the generations, as seems to be required by the experimental flavor constraints. These states could be discovered, or excluded, in future experiments at the Tevatron or LEP II. There is already an interesting constraint arising from FNAL data, since at minimum there are two degenerate states containing an electron in combination with either a 1st or 2nd generation quark. From the D0 bound on leptoquarks which couple to electrons [12] the total production cross section to these states has to be less than 0.4 pb, which translates to a limit of $M_{LQ} > 190$ GeV. Degenerate with these states will be leptoquarks composed of $\mu q$ and $\tau q$, although the present bounds on such states are much weaker.

Note added. While this paper was in preparation, several other papers inspired by the high-$Q^2$ HERA anomaly appeared [17]. Compared to other authors, we appear to place greater emphasis on the unusual flavor structure required.

Acknowledgments

We wish to thank M. Barnett, I. Hinchliffe, S. Ritz, F. Sciulli, S. Treiman, and E. Weinberg for useful conversations.
References

[1] H1 Collaboration, report DESY-97-024, (February 1997) [hep-ex/9702012].
[2] ZEUS Collaboration, report DESY-97-025, (February 1997) [hep-ex/9702015].
[3] CDF Collaboration, Phys. Rev. Lett. 77 (1996) 438.
[4] H1 Collaboration, report DESY-94-248 (December 1994); see also Phys. Lett. B369 (1996) 173.
[5] S. Adler, report IASSNS-HEP-97/12 (February 1997), [hep-ph/9702378].
[6] See e.g. K. Maeshima, for the CDF Collaboration, report FERMILAB-CONF-96/412-E, Proc. ICHEP’96, Warsaw 1996.
[7] S. Capstick and S. Godfrey, Phys. Rev. D37 (1988) 2466.
[8] CTEQ Collaboration, H.L. Lai, et al, Phys. Rev. D51 (1995) 6139.
[9] S. Komamiya, talk given at CERN on 25 Feb. 1997 [http://www1.cern.ch/Opal/plots/komamiya/koma.html].
[10] Particle Data Group, Phys. Rev. D54 (1996) 1.
[11] W. Buchmuller, R. Ruckl and D. Wyler, Phys. Lett. B191 (1987) 442.
[12] J. Wightman (D0 Collaboration), talk at Les Recontres de la Vallee d’Aoste, March 2–8, 1997.
[13] J. Hewett and S. Pakvasa, Phys. Rev. D37 (1988) 3165.
[14] See, for example:
M. Leurer, Phys. Rev. D49 (1994) 333;
S. Davidson, D. Bailey and B. Campbell, Zeit. fuer Physik C61 (1994) 613.
[15] J. Hewett, et al, in Proceedings of the Workshop on Physics at Current Accelerators and the Super-colliders, Argone 1993, [hep-ph/9310361].
[16] See, for example, D. Choudhury and S. Raychaudhuri, report CERN-TH-97-026 (Feb. 1997), [hep-ph/9702392], and references therein.
[17] G. Altarelli et al, report CERN-TH/97-40 (March 1997) [hep-ph/9703276];
H. Dreiner and P. Morawitz, (March 1997) [hep-ph/9703279];
M. Doncheski and S. Godfrey, report OCIP/C 97-02 (March 1997) [hep-ph/9703285];
J. Blumlein, report DESY-97-032 (March 1997), [hep-ph/9703287];
J. Kalinowski et al, report DESY-97-038 (March 1997) [hep-ph/9703288].