Four-Fermion Effective Interactions and Recent Data at HERA

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Abstract: We discuss the possibility of explaining the excess in the cross section at high-$Q^2$ recently found at HERA in terms of four-fermion effective interactions. To avoid the constraints from low-energy data, we select three special cases in which the contact interaction is a product of vector-vector, axial-axial and vector-axial currents. For these a satisfactory fit of HERA data is possible, while keeping agreement with LEPII and CDF data, for an interaction scale $\Lambda = 3.5$ TeV. As the statistics of the experiments improves—and if the effect persists—it will be soon possible to discriminate between such contact terms and the alternative explanation in terms of leptoquark exchange.

Keywords: LEP, HERA and SLC Physics, Deep Inelastic Scattering, Phenomenological Models.
1 Introduction

The excess in the neutral current cross section at large momentum transfered $Q^2$ recently announced at HERA [1, 2] allows us, while we wait for an improvement in the statistics, to speculate about physics beyond the standard model in a concrete setting.

Actually, most of the territory is already well mapped and the theoretical analysis needed is available in the preliminary work done in view of the experimental runs at HERA [3] and in the older papers cited therein.

Such references convincingly argue that any excess in the cross section similar to the one contained in the recent HERA data, can arise either because of the exchange of a leptoquark, and has in this case the shape of a resonance produced in the $s$-channel, or because of the presence of an effective four-fermion interaction, and has the shape of a continuum in the $t$-channel instead. In this letter we would like to investigate the latter possibility and then briefly compare the two.

That the presence of an effective four-fermion interaction could lead, via interference with the Standard Model amplitude, to an increase in the cross section was first pointed out in [4]. Such an interaction could originate from quark substructure or, more generally, by the exchange among quarks and leptons of a heavy particle like, for instance, an extra $Z'$ boson. Since the scale of such hypothetical new exchange is much higher than that probed at HERA, we only see the contribution of the effective four-fermion terms thus generated. Their form can in principle be rather complicated, as it is the case for weak interactions in the Standard Model (an example of which is the low-energy effective $\Delta S = 1$ lagrangian).

As it is natural, as we were working on our paper, several works appeared discussing HERA data. Two of them are comprehensive analyses [5, 6], others are more specific to the leptoquark scenarios [7, 8, 9, 10, 11]. Finally, one work [12] is very close to our approach and concentrates on four-fermion interactions; it reaches conclusions that, although not completely equivalent, agree with ours.
2 Low Energy Data and Contact Interactions

In this section, we review the constraints on the four-fermion couplings coming from the low-energy neutral current data. In particular, we will see that atomic parity violation imposes quite severe bounds [13].

The most general helicity-conserving four-fermion contact interaction among leptons and quarks is:

\[
L^4_f = \sum_{i,j=L,R} \eta^{q}_{ij} \bar{e}_i \gamma_\mu e_i (\bar{q}_j \gamma^\mu q_j) \tag{2.1}
\]

It is conventional to write the couplings \( \eta^{q}_{ij} \) as

\[
\eta^{q}_{ij} = \frac{\pm 4\pi}{(A^{q}_{ij})^2} \tag{2.2}
\]

At HERA, the relevant operators are for \( q = u, d \), and therefore there are in general eight independent couplings allowed.

These eight couplings are reduced to six if we impose \( SU(2)_L \) invariance, giving the constraints:

\[
\eta^u_{LL} = \eta^d_{LL} \quad \text{and} \quad \eta^u_{RL} = \eta^d_{RL} \tag{2.3}
\]

It is important to remark that \( SU(2)_L \) invariance gives a neutrino-quark four-fermion interaction, of the form

\[
L^{\nu q} = (\bar{\nu}_L \gamma_\mu \nu_L) \left[ \eta^{\nu}_{LL} Q_L \gamma^\mu Q_L + \eta^{\nu}_{LR} \bar{u}_R \gamma^\mu u_R + \eta^{\nu}_{RL} \bar{d}_R \gamma^\mu d_R \right] \tag{2.4}
\]

where \( Q_L \) is the \((u_L, d_L)\) doublet. The interaction (2.4) can produce effects in \( \nu\)-nucleon deep inelastic scattering, as discussed in detail below.

The low-energy parity-violating electron-quark interaction is usually written by introducing the coefficients \( C_{i q} \), \( i = 1, 2, q = u, d \), defined as

\[
L_{eq} = \frac{G_F}{\sqrt{2}} \left[ \bar{e}_i \gamma_5 e_j \left( C_{1u} \bar{u}_i \gamma^\mu u_j + C_{1d} \bar{d}_i \gamma^\mu d_j \right) + \bar{e}_i \gamma_\mu e_j \left( C_{2u} \bar{u}_i \gamma_5 u_j + C_{2d} \bar{d}_i \gamma_5 d_j \right) \right] \tag{2.5}
\]

The data on \( C_{1q} \) expressed in terms of the so-called weak charge \( Q_W \)

\[
Q_W = -2 \left[ C_{1u}(2Z + N) + C_{1d}(Z + 2N) \right] \tag{2.6}
\]

which is measured with a precision of about \( \sim 1.0\% \) in the isotope 133 of Cesium [14]

\[
Q_W(Cs) = -72.11 \pm 0.27 \pm 0.89 \tag{2.7}
\]

Concerning the coefficients \( C_{2q} \), only the combination

\[
C_{2u} - \frac{1}{2} C_{2d} = -0.04 \pm 0.13 \tag{2.8}
\]

is measured [13].
The four-fermion interaction (2.1) gives the following contributions to the $C_{ij}$'s

$$
\Delta C_{1q} = \frac{1}{2\sqrt{2}G_F} (-\eta^q_{LL} - \eta^q_{LR} + \eta^q_{RL} + \eta^q_{RR})
$$

$$
\Delta C_{2q} = \frac{1}{2\sqrt{2}G_F} (-\eta^q_{LL} + \eta^q_{LR} - \eta^q_{RL} + \eta^q_{RR})
$$

(2.9)

As previously stated, the most stringent constraint on the $\eta^q_{ij}$ comes from the measure of the weak charge (2.6): assuming for simplicity $\eta^u_{ij} = \eta^d_{ij}$, in absence of cancellation (i.e. turning on only one $\eta_{ij}$) one has

$$
|\Delta Q_W(C_s)| \simeq \left(\frac{17 \text{ TeV}}{\Lambda_{ij}}\right)^2
$$

(2.10)

Therefore one easily gets a lower bound on $\Lambda$ of the order of 15 TeV, a scale too high to be probed at HERA.

To escape the bound (2.10), we will select three scenarios: a vector-vector (VV) interaction, with

$$
\eta_{LL} = \eta_{RR} = \eta_{LR} = \eta_{RL} \equiv \eta_{VV}
$$

(2.11)

an axial-axial (AA) interaction, with

$$
\eta_{LL} = \eta_{RR} = -\eta_{LR} = -\eta_{RL} \equiv \eta_{AA}
$$

(2.12)

and finally the product of a leptonic vector current with an axial quark current (VA), with

$$
-\eta_{LL} = \eta_{RR} = \eta_{LR} = -\eta_{RL} \equiv \eta_{VA}
$$

(2.13)

The first two possibilities are parity-conserving, and therefore do not contribute to the $C_i$: the last one (VA) contributes only to the $C_2$, not to the weak charge. One finds

$$
\Delta \left( C_{2a} - \frac{1}{2} C_{2d} \right) \simeq \left(\frac{0.87 \text{ TeV}}{\Lambda_{VA}}\right)^2
$$

(2.14)

that means, see (2.8), a lower bound on $\Lambda_{VA}$ of the order of 2 TeV.

There also other possible combinations of couplings avoiding the atomic parity violation bounds, like for instance the one considered in [12]

$$
\eta_{LR} = \eta_{LL} = 0
$$

(2.15)

or a possible cancellation between the $u$ and $d$ contribution to $Q_W$. To keep the discussion simpler, we shall restrict ourselves to the three mentioned cases, and we will assume the same couplings to the $u$ and $d$ quarks. In [13] it is noticed that approximate global symmetries other than parity can eliminate the contribution of contact terms to atomic parity violation.

If we require a $SU(2)_L$ invariant interaction, there is a neutrino-quark four fermion term inducing possible deviations in $\nu$-nucleon deep-inelastic scattering experiments. We
stress however that, being the measurements done with muon neutrinos, the data can constrain only a $(\nu_\mu \nu_\mu)(qq)$ ($q = u, d$) contact term and therefore do not strictly apply to our analysis. One has to take into account this constrain if the interaction is family blind, as for instance in the case of an universally coupled heavy $Z'$. In such a situation the relevant lagrangian is, following the standard parameterization:

$$\mathcal{L}_{\nu q} = \frac{G_F}{\sqrt{2}} \bar{\nu} \gamma^\mu (1 - \gamma_5) \nu \times \sum_i \left[ \epsilon_L(i) \bar{q}^i \gamma_\mu (1 - \gamma_5) q^i + \epsilon_R(i) \bar{q}^i \gamma_\mu (1 + \gamma_5) q^i \right]$$ (2.16)

The presence of the interaction (2.4) will modify the standard model values of the coefficients $\epsilon_i(q)$, inducing the following deviations:

$$\Delta \epsilon_L(q) = -\frac{1}{2\sqrt{2}G_F} \eta_{LL}$$

$$\Delta \epsilon_R(q) = -\frac{1}{2\sqrt{2}G_F} \eta_{LR}$$ (2.17)

Numerically, the expected deviation is of the order

$$\Delta \epsilon_i(q) \simeq \left( \frac{0.62 \text{ TeV}}{\Lambda} \right)^2,$$ (2.18)

which gives a lower bound on $\Lambda$ roughly of the order of 4 TeV or larger [17].

3 Four-Fermions Interactions at HERA

We will now examine the effects of the interaction (2.1) at the colliders, and in particular we will try to see if it has the potentiality to explain the HERA excess. As explained in the previous section, we will limit our analysis to the combinations of couplings (2.11), (2.12) and (2.13).

We examine first the sensitivity of HERA to the different contact interactions in the $e^+p$ neutral current channel. In fig. 1 and 2, we plot the ratio of the differential cross section $d\sigma/dQ^2$ including contact terms to the Standard Model differential cross section. The contact terms have a $\Lambda = 3.5$ TeV, and we assume the same contact terms for $u$ and $d$ quarks. To avoid constraints from $\nu_\mu$ DIS and from the combined Tevatron data, we do not assume the same contact terms for muons. The signs of the contact terms coefficients in fig. 1 are such to give the maximum enhancement of the cross section, that is to interfere constructively with the Standard Model contribution. This is obtained by taking $\eta_{VV} = \eta_{VV}^+ > 0$, $\eta_{AA} = \eta_{AA}^- < 0$ and $\eta_{VA} = \eta_{VA}^+ > 0$ respectively in (2.11), (2.12) and (2.13). As one can see from the figure, the $VV$ contact interaction provides the biggest effect, the $AA$ interaction is almost as big, and the $VA$ contact interaction has approximately the same influence as the $LR$ contact interactions, which is, among the chiral interaction $LL$, $LR$, $RL$ and $RR$, the one most constrained by HERA [18]. Of
Figure 1: Effect of different contact interactions with constructive interference with the Standard Model on the differential cross section $d\sigma/dQ^2$ as a function of $Q^2$ in GeV$^2$. The scale of the contact interactions is $\Lambda = 3.5$ TeV.

course the chiral interaction is excluded by the atomic parity violation data, and we have put it in the figure only for comparison with previous analyses.

The importance of the interference effect is evident in fig. 2, where we have changed the signs of the contact term coefficients, plotting as in fig. 1 the ratio of the differential cross section $d\sigma/dQ^2$ to the Standard Model. Now the terms $\eta_{VV}^-$ and $\eta_{AA}^+$ reduce the Standard Model cross section, while $\eta_{VA}^-$ is rather insensitive to the sign and gives an excess comparable to $\eta_{VA}^+$. In other terms, the interference is quantitatively very important for the $VV$ and $AA$ cases, whereas it is negligible for the $VA$ contact term.

Looking for an enhancement at HERA, we will obviously choose the signs of the contact terms as those in fig. 1.

Beside HERA, the electron-quark interactions can potentially give effects at CDF, in the production of electron pairs, and at LEPII, in the hadronic cross section. At LEP I, there is a one-loop potential effect on the $Z^0$ leptonic width [19]. As also noticed in [12], the Standard Model amplitude changes sign under crossing from the $t$ channel $eq \rightarrow eq$ to the $s$ channel $e^+e^- \rightarrow q\bar{q}$ (LEPII) or $q\bar{q} \rightarrow e^+e^-$ (CDF). Therefore, by choosing the signs of the contact terms to interfere constructively at HERA, we obtain destructive interference at LEPII and CDF. This consideration helps to better understand the LEPII limits on the contact interactions.

By looking at possible deviations in the hadronic cross section, the OPAL collaboration [20] has obtained the following limits

$$\Lambda_{VV}^- > 3.3 \text{ TeV} \quad ; \quad \Lambda_{VV}^+ > 2.9 \text{ TeV}$$
Figure 2: Effect of different contact interactions with destructive interference with the Standard Model on the differential cross section $d\sigma/dQ^2$ as a function of $Q^2$ in GeV$^2$. The scale of the contact interactions is $\Lambda = 3.5$ TeV

$$\Lambda_{\bar{A}A}^+ > 2.8 \text{ TeV} \quad ; \quad \Lambda_{AA}^- > 3.5 \text{ TeV}$$

(3.1)

These bounds assume that the contact interaction is universal for all five quarks produced at LEP II, and are weakened if only the first family quarks $u, d$ are involved: in any case the ones concerning this analysis, $\Lambda^+_{VV}$ and $\Lambda^-_{AA}$, are below the scale we will assume, that is 3.5 TeV.

The Drell-Yan production of $e^+e^-$ pairs at CDF is another constraint to be taken into account. As stated before, the chosen contact terms will interfere destructively in this process. A recent analysis [21] quotes the 95% CL limits only on the left-left (LL) contact interaction scale $\Lambda_{LL}$: $\Lambda_{LL}^- > 3.4$ TeV, $\Lambda_{LL}^+ > 2.4$ TeV. We have checked that the interaction $\Lambda_{VV}^+ = 3.5$ TeV, $\Lambda_{AA}^- = 3.5$ TeV and $\Lambda_{V\Lambda}^+ = 3.5$ TeV is still compatible with these CDF bounds, even if very close to the exclusion region. We remark that by assuming the same contact scale for the muons, i.e. a term $(\mu\mu)(qq)$ originating for instance from a heavy $Z'$, the combined muon and electron CDF data give a stronger bound, excluding the value $\Lambda = 3.5$ TeV for the selected interactions.

Having checked that HERA is very sensitive to the chosen forms of the contact interaction, and that the chosen $\Lambda = 3.5$ TeV is compatible with low-energy and colliders data, we try now to see if the excess of high-$Q^2$ neutral current events reported at HERA could be explained by a contact interaction.

In fig. 3 we look at the $Q^2$ distribution of the events by integrating from a given minimum value $Q_{0}^2$. The standard model prediction, given by the solid black line, is shown to lie below the combined data of H1 and ZEUS (the black dots and the gray error
bars of the figure) and the introduction of four-fermion interactions, represented by the gray lines, is shown to help in explaining most of the discrepancy.

Of course, the introduction of a leptoquark exchange would also reproduce the behavior of experimental data, as shown in [5].

In a way, fig. 3 is rather compelling in pointing toward an actual discrepancy between the standard model prediction and the data.

Figure 3: Integrated cross section for $Q^2 > Q_0^2$ versus $Q_0^2$ in GeV$^2$. The Standard Model (SM) prediction (the black line) is compared with the contact interactions VV, AA and VA (with $\Lambda = 3.5$ TeV) and with the HERA data (H1 plus ZEUS).

Because of the integration over the values of $Q^2$, fig. 1 does not help us much in comparing different scenarios, in particular leptoquark versus contact interaction scenarios. A more discriminating way of plotting data and theoretical predictions consists in showing the cross sections versus the invariant mass.

To better understand such a plot, let us recall the kinematics of deep inelastic scattering at HERA. In addition to the transferred momentum $Q^2$, there is another independent variable, that can be, for instance the Bjorken variable

$$x \equiv \frac{Q^2}{2(P \cdot q)}$$

which itself leads to the invariant mass

$$M = \sqrt{x s}$$

where $s$ is the center-of-mass energy squared, at HERA of about $(300 \text{ GeV})^2$, or

$$y = \frac{M^2}{x s}.$$
Fig. 4 shows the differential cross sections \( d\sigma/dM \), with the cuts \( Q^2 > 15000 \text{ GeV}^2 \) and \( 0.1 < y < 0.9 \), for various scenarios. The lowest line (black) is the Standard Model prediction. The VV and VA contact interactions with \( \Lambda = 3.5 \text{ TeV} \) are the gray lines, respectively continuous and dashed. The AA line, being quite similar to the VV one, is not shown. Moreover, we have plotted the cross section with exchange of a leptoquark with mass of 200 GeV as the dash-dotted line. In this case of course one can see the resonance in the \( s \)-channel rising sharply at \( M = 200 \text{ GeV} \). The leptoquark is a scalar \( \phi \) coupled to the \( d \) quark only

\[
\lambda \phi \bar{d} R e_L + h.c.
\]  

with a value of coupling \( \lambda = 0.04 \), as indicated by the HERA data [5, 9, 10]. This leptoquark is by convention named as \( \tilde{R}_{2L} \) [22] or \( \tilde{S}_{1/2} \) [23], and it is a very narrow state:

\[
\Gamma = \frac{1}{16\pi} \lambda^2 m_{LQ} = 6.37 \text{ MeV}
\]

Therefore, for values of the invariant mass \( M \) different from 200 MeV, the leptoquark scenario, as far as fig. 4 is concerned, is the same as the Standard Model. On the other hand, the excess for the contact interaction is distributed over the entire \( M \) range.

Figure 4: Differential cross section for various scenarios: contact interactions VV e VA, with \( \Lambda = 3.5 \text{ TeV} \), and scalar leptoquark (LQ), with coupling \( \lambda = 0.04 \). The cuts \( Q^2 > 15000 \text{ GeV}^2 \) and \( 0.1 < y < 0.9 \) are applied.

In order to compare with the experimental data, we have integrated the differential cross sections of fig. 4 per bins of width 25 GeV, computing the expected number of events per bin at HERA. The histograms are presented in fig. 5 and 6. As in fig. 4, there is a cut at \( Q^2 > 15000 \text{ GeV}^2 \): we have combined the H1 and ZEUS data, for a total of 24 events.
passing the cut, taking into account of the efficiencies of $\sim 80\%$. The $M$ distribution of the H1 excess is peaked around $M = 200$ GeV, while the ZEUS data are more evenly distributed. Moreover, there is also a discrepancy in the number of events seen by the two experiments and it has been argued \cite{24} that the two experiments are compatible with a probability of less $1\%$.

Figure 5: Events per bin vs. mass invariant: the VV four-fermion effective interaction scenario (gray line) versus the Standard Model (black line), with the cut $Q^2 > 15000$ GeV$^2$.

In fig. 5, we present the histogram of the expected events for a VV contact interaction with $\Lambda = 3.5$ TeV (gray line), together with the Standard Model expectation (black line). The VV contact interaction produces a distribution in $M$ quite similar in shape to the Standard Model, and accounts reasonably well for the data. The only discrepancy is seen in the bin centered at $200$ GeV, because of the seven H1 events clustered around that value of $M$.

Fig. 6 presents the leptoquark scenario, which provides an excess only in the bin centered at $M = 200$ GeV, while agrees with the Standard Model elsewhere.

We think it is fair to say that the experimental situation does not exclude at the moment either the leptoquark or the contact interaction scenario, and that only more data will clarify the situation. Only then we will also know for sure whether we are in the presence of an actual discrepancy with the Standard Model or a simple statistical fluctuation.

Forthcoming analyses at Tevatron are expected to improve the bounds both on leptoquark and contact interaction scenarios, and might even exclude them. On the other hand the improvement in statistics at HERA will clarify the situation, as it can be readily understood by looking at fig. 5 and 6. If the new data will be such to spread evenly in $M$
Figure 6: Events per bin vs. mass invariant: the leptoquark scenario (gray line) versus the Standard Model (black line), with the cut $Q^2 > 15000 \, \text{GeV}^2$.

the excess, than the contact interaction scenario will be preferred, on the other hand, if the clustering at $M = 200 \, \text{GeV}$ will persist and be enhanced, then it is clear that we will be looking at a leptoquark. Finally, if the new data will substantially reduce the number of events in excess, the Standard Model will come out unchallenged one more time.

Acknowledgments

We would like to thank Ferruccio Feruglio for discussions and Ann Nelson for a relevant remark on neutrino contact interactions.
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