Contact Interaction Explanation of HERA Events

and $SU(3)_C \times SU(2)_L \times U(1)_Y$ Invariance

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Abstract

We reexamine the contact interaction hypothesis for excess high-$Q^2$ events seen at HERA in $e^+ p \rightarrow e^+ X$ scattering. We consider the most general structure of contact interactions insisting on $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariance. Apart from constraints for $e^+ e^- \rightarrow q\bar{q}$, Drell-Yan and atomic parity violation experiments, we find stringent constraints from neutrino deep inelastic data, provided one assumes lepton universality. A possible choice of contact terms that escape present bounds is still possible, although new data from FERMILAB and LEP should further constrain such a possibility.

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Many explanations of the excess in $e^+p \to e^+X$ scattering events observed at large $Q^2$ at HERA \[1\] have been offered in the literature \[2\]. These explanations either call for one or more s channel leptoquark added to the Standard Model (SM) or embedded within supersymmetric framework, or call for contact interactions that may arise due to an exchange of heavy particles beyond the SM. A statistical fluctuation from the SM can also not be ruled out.

In this note we shall pursue the hypothesis that the excess of events arises due to contact interactions. These interactions can come from exchange of particles in s or t channel, and we consider the most general structure. Any physics beyond the SM must necessarily respect the low energy $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry. We thus impose this symmetry on all the new terms. This symmetry along with the lepton universality allows us to use neutrino data to arrive at more stringent limit than those considered previously \[3,4\]. Reference \[5\] also invokes this symmetry but does not strictly impose the constraints on the solutions.

Under the SM gauge group, the left-handed ($Q_L$), right-handed ($U_R$, $D_R$) quarks and left-handed ($L_L$), right-handed ($E_R$) leptons transform as:

$$Q_L : (3, 2, 1/3) ; U_R : (3, 1, 4/3) ; D_R : (3, 1, -2/3) ;$$

$$L_L : (1, 2, -1) ; E_R : (1, 1, -2) .$$

(1)

Contact interactions relevant to HERA data must contain quarks and leptons. The following is a list of the allowed quark-lepton contact interactions invariant under the SM gauge symmetry \[6\]:

$$O_{LL} = \bar{L}_L\gamma^\mu L_L\bar{Q}_L\gamma_\mu Q_L ; O_{UR}^u = \bar{e}_R\gamma^\mu e_R\bar{u}_R\gamma_\mu u_R ;$$

$$O_{RR}^d = \bar{e}_R\gamma^\mu e_R\bar{d}_R\gamma_\mu d_R ; O_{RL} = \bar{e}_R\gamma^\mu e_R\bar{Q}_L\gamma_\mu Q_L ;$$

$$O_{LR}^u = \bar{L}_L\gamma^\mu L_L\bar{e}_R\gamma_\mu u_R ; O_{LR}^d = \bar{L}_L\gamma^\mu L_L\bar{d}_R\gamma_\mu d_R ;$$

$$O_V = \bar{Q}_L\gamma_\mu L_L\bar{e}_R\gamma^\mu d_R ; O_S = \bar{Q}_L e_R\bar{L}_L u_R ;$$

$$O_{LL}^3 = \bar{L}_L\gamma_\mu L_L\bar{Q}_L\gamma_\mu Q_L\epsilon_{ijkl} .$$

(2)

and parameterize the effective Lagrangian added to the SM Lagrangian as
Here $i$ runs the same indices as the indices of the operators in equation (2). The parameters $\eta_i$ represent the strength for the new interactions. Assuming CP conservation in these contact interactions, $\eta_i$ are real and can have positive or negative signs. We are mostly concerned about the first generation contact terms in (3), however in order to use CCFR limits, we shall make the assumption of lepton universality.

There are many possible mechanisms which can generate the above listed contact interactions. Exchanges of super heavy particles such as $Z'$, vector leptoquark, scalar leptoquark are some of the possibilities.

Let us now analyse which operators that are relevant to HERA data. We first consider operators $O_{V,S}$. The strength of these two operators are severely constrained from low energy data on $\pi^- \to e\bar{\nu}$ because they lead to enhanced matrix elements compared with the SM contribution. A simple estimate gives

$$< e\bar{\nu} | O_V | \pi^- > = -2\bar{e}_R \nu_L < 0 | \bar{u}_L d_R | \pi^- > = i \sqrt{2} f_\pi \frac{m_\pi^2}{m_u + m_d} \bar{e}_R \nu_L ,$$

$$< e\bar{\nu} | O_S | \pi^- > = -\frac{1}{4} < e\bar{\nu} | O_V | \pi^- > ,$$

(4)

where $f_\pi = 93$ MeV is the $\pi$ decay constant.

It has been shown that the SM prediction for $\pi^- \to e\bar{\nu}$ agrees with the experimental data within 1% \cite{7}. Requiring that new physics does not change the SM result by more than 1%, we find that $\eta_V$ and $\eta_S$ are constrained to be less than $0.5 \times 10^{-4}$ (GeV$^{-2}$) and $2 \times 10^{-4}$ (GeV$^{-2}$), respectively. With these bounds, the effects of $O_V$ and $O_S$ are too small to have any impact on HERA data.

The remaining contact interactions are in fact of the same type as analysed in Ref. \cite{3} for $e\bar{e}q\bar{q}$ contact interactions. However, because the requirement that the contact interactions be invariant under $SU(3)_C \times SU(2)_L \times U(1)_Y$, there are several fundamental differences. We note that $\eta_{eu}^{RL} = \eta_{ed}^{RL} = \eta_{RL}$, and for left-handed electron in the $e\bar{e}q\bar{q}$ interactions, there are also associated $\nu\bar{\nu}qq$ interactions. These constrain the interactions further.
We now analyse the high-$Q^2$ $e^+ p$ events at HERA. The cross section for $e^+ p \rightarrow e^+ X$ is given by

\[
\frac{d\sigma(e^+ p)}{dx dy} = \frac{s x}{16\pi} \{ u(x, Q^2) [|M_{eu}^{LR}|^2 + |M_{eu}^{RL}|^2 + (1 - y)^2(|M_{eL}^{LL}|^2 + |M_{eL}^{RR}|^2)] \\
+ d(x, Q^2) [|M_{ed}^{LR}|^2 + |M_{ed}^{RL}|^2 + (1 - y)^2(|M_{eL}^{LL}|^2 + |M_{eL}^{RR}|^2)] \},
\]

where $Q$ is the momentum transfer, $u(x, Q^2)$ and $d(x, Q^2)$ are the u and d quark parton distributions, and

\[
M_{ij}^q = -\frac{e^2 Q_i Q_j}{sx y} \frac{g_Z^2 (T_{e_i}^3 - \sin^2\theta_W Q_e)(T_{q_j}^3 - \sin^2\theta_W Q_q)}{sx y + m_Z^2} + \eta_{ij}^q.
\]

Here $Q_f$ and $T_i^3$ are charges and weak isospin, respectively, $g_Z = e/(\sin\theta_W \cos\theta_W)$, $P$ and $q$ are the incoming proton and positron momentum, respectively, and $s$ is the CM energy-squared.

Using CTEQ-3 parton distribution functions, we find that to explain the excess of events at HERA, the size of the contact terms necessary taking them singly, is $\eta_{uLR}^u, \eta_{RL}^u$ approximately 1.5 TeV$^{-2}$, $\eta_{uLR}^d$ approximately 6 TeV$^{-2}$. Contact terms of the type $\eta_{LL}^u, \eta_{LL}^d, \eta_{RR}$ have to be much larger, approximately 8 TeV$^{-2}$ because these contributions are suppressed by the factor $(1 - y)^2$ and favor excess events at low $y$. Experimental data for the $y$ distribution of the excess events clearly favors excess events at high $y$.

Possible solutions to HERA events must satisfy constraints from other experimental data. We now consider the limits on the contact interactions from $e^+ e^-$ collider data at LEP. Table 1 gives the OPAL preliminary 95% C.L. limits on various contact terms converted to our notation. Similarly in Table 2 we give the CCFR limits remembering that the data was from neutrino on iron target, which has roughly equal numbers of neutrons and protons. The limits on $\eta_{LL}, \eta_{LL}^u, \eta_{LR}^u$ and $\eta_{LR}^d$ are much stronger from CCFR than those from OPAL.

Finally we have extremely strong limits from atomic parity violation parameter $Q_W$. For $^{133}_{55}$Cs, we have for change in $Q_W$ from the SM:
\[ \Delta Q_W = (11.4 \text{TeV}^2)(\eta_{LL}^3 + \eta_{LL} + \eta_{LR}^u - \eta_{RL}^u - \eta_{RR}^u) \]
\[ + (12.8 \text{TeV}^2)(\eta_{LL} + \eta_{LR}^d - \eta_{RL}^d - \eta_{RR}^d) . \]  

(7)

Experimental measurements find \( Q_W = -72.11 \pm 0.93 \) \([\Xi]\) while the SM prediction for \( m_t = 175 \text{ GeV} \) and \( m_H = 100 \text{ GeV} \) is \( Q_{SM}^W = -73.04 \). It is clear that the difference \( \Delta Q_W = 1.09 \pm 0.93 \) places a severe constraint on the allowable contact interactions, and it can not accommodate any single contact term.

It is clear that any solutions with \( O_{LL} \) or \( O_{LL}^3 \) term giving significant contribution to the HERA events are ruled out because large \( \eta_{LL} \) or \( \eta_{LL}^3 \) required are in conflict with OPAL and CCFR data. It is however possible to have solutions with significant contribution from \( O_{LR} \) or \( O_{RL} \). Given that we need significant \( \eta_{LR} \) or \( \eta_{RL} \) couplings to explain HERA data, we can try to obtain solutions that satisfy all the constraints. The following are two types of solutions:

**Solution A**

\[ \eta_{LR} = \eta_{RL} = \eta_{LL}^3, \]
\[ \eta_{LL} = \eta_{LL}^3 = \eta_{LR}^d = \eta_{RR}^d = 0 . \]  

(8)

This solution corresponds to the one first suggested by Ref. \([\Xi]\) and also discussed in Ref. \([\Xi]\). However note that we must include both \( u \) and \( d \) quark contributions because of gauge invariance requirement and we are restricted to having \( \eta_{LR}^u \) and \( \eta_{LR}^d < 1.01 \text{ TeV}^{-2} \) from CCFR data. This solution is barely able to explain the excess events. We note that Ref. \([\Xi]\) preferred a values of \( \eta_{LR}^u \approx 1.4 \text{ TeV}^{-2} \). Analysis of new data from FERMILAB is expected to improve this bound significantly making this solution probably inadmissible.

**Solution B**

\[ \eta_{RL} = -\eta_{RR}^u = -\eta_{RR}^d, \]
\[ \eta_{LR}^u = \eta_{LR}^d = \eta_{LL} = \eta_{LL}^3 = 0 . \]  

(9)

The most stringent limit now comes from OPAL and Drell-Yan process. However, \( \eta_{RL} \approx 1.5 \text{ TeV}^{-2} \) is clearly acceptable. In Figure 1 we plot \( \sigma(Q^2 > Q_{min}^2) \) as a function of \( Q_{min}^2 \) for
this and compare it with SM and data. Since we have $\eta_{RR}^u$ and $\eta_{RR}^d$ terms, the $y$ distribution is now altered. However, the change is not significant and this choice is consistent with data. To demonstrate this, in Figure 2 we show the $y$ distribution of events expected with addition of contact terms and compare it with the SM. In Figure 3 we show the Drell-Yan process with the contact term and compare it to the SM. In the region of invariant dilepton mass up to 300 GeV there is little deviation from the SM, and CDF data is in excellent agreement [1]. Beyond that, between 400 GeV to 800 GeV, contact interactions produce an excess of events which for integrated luminosity of 110 $pb^{-1}$ are approximately 10 compared to 1 in SM. Data at present is consistent with SM, though one can not rule out contact interaction. Further gain in luminosity will constrain this model, making this explanation of HERA data unacceptable.

In the above, we have assumed that the contact interactions only involve the first generation of quarks. In general the contact interactions will also involve other generations. If these interactions are due to leptoquark exchange, the couplings involving different generations can have different strength. It is possible that couplings to other generations are small and will not cause any difficulties. However, if the contact interactions are due to exchange of $Z'$ particles [2] with universal coupling to different generations (leptons and quarks), the contact interaction explanation of the excess events at HERA could be in trouble because the constraints from various experiments become even tighter.

For example, a class of $Z'$ models inspired by string theories based on $E_6$ even without coupling constant constraint from GUT is ruled out. These models have charges given by $Q(\alpha) = Q_\psi \cos(\alpha) + Q_\chi \sin(\alpha)$, where $Q_\psi$ and $Q_\chi$ are the charges of $U(1)_\psi$ and $U(1)_\chi$ subgroup of $E_6$ symmetry. The contact interaction generated by this model is

$$\eta_{ij}^0 = \eta_0 Q_i^l(\alpha) Q_j^q(\alpha),$$

$$Q_L^e(\alpha) = -Q_R^e(\alpha) = Q_R^\nu(\alpha) = \cos(\alpha) + \sin(\alpha) \sqrt{\frac{3}{5}},$$

$$Q_R^e(\alpha) = -Q_L^e(\alpha) = Q_L^\nu(\alpha) = -Q_L^d(\alpha) = -[\cos(\alpha) - 3 \sqrt{\frac{3}{5}} \sin(\alpha)], \quad (10)$$
and $\eta_0$ is an arbitrary free parameter since we do not impose constraints from coupling unification. Constraint from $Q_W$ now yields,

$$\Delta Q_W = \eta_0 (102.4) \text{TeV}^2 \left[ \sqrt{3} \cos \alpha \sin \alpha - \frac{3}{5} \sin^2 \alpha \right].$$  \hspace{1cm} (11)

$\eta_0$ has to be of order 1 TeV$^{-2}$ to explain HERA data and the only acceptable solutions are $\tan \alpha = 0$ and $\sqrt{5}/3$. By considering $\eta_{LL}$, neutrino deep inelastic scattering data now yields a bound on $\eta_0$ to be less than 0.5 TeV$^{-2}$ for $\alpha = 0$ and 0.3 TeV$^{-2}$ for $\tan \alpha = \sqrt{5}/3$. Further, LEP $e^+e^-$ data imposes strong constraint on $\eta_0$ for $\tan \alpha = \sqrt{5}/3$ solution, requiring $\eta_0 < 0.15$ TeV$^{-2}$ from the requirement that cross-section at large $s$ shall not deviate from SM by more than 6%.

In conclusion, we have examined the contact interaction explanation for high-$Q^2$ events seen at HERA in $e^+p \rightarrow e^+X$ scattering. We considered the most general structure of contact interactions invariant under $SU(3)_C \times SU(2)_L \times U(1)_Y$. Experimental data from $e^+e^- \rightarrow q\bar{q}$, Drell-Yan, deep inelastic neutrino-nucleon processes, and atomic parity violating interactions place severe bounds on the strengths of contact interactions. Assuming the contact interactions only involve the first generation of leptons and quarks, we found that there are solutions which escape present bounds although new data from FERMILAB and LEP should further constrain such possibility. Contact interactions generated by $Z'$ exchange are more stringently constrained.

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Table 1

|    | $e^+e^- \rightarrow u\bar{u}$ | $e^+e^- \rightarrow d\bar{d}$ |
|----|--------------------------------|--------------------------------|
| $\eta_{LL}$ | 10.4 | 2.2 |
| $\eta_{LL}^3$ | 10.4 | 2.2 |
| $\eta_{RL}$ | 6.4 | 4.4 |
| $\eta_{RR}$ | 2.9 | 8.7 |
| $\eta_{RL}$ | 4.0 | 6.4 |
| $\eta_{LR}$ | 4.4 | 6.4 |
| $\eta_{LR}$ | 4.4 | 6.4 |

**Table Caption:** OPAL 95% C.L. limits on contact interactions. The signs + and - indicate the signs of $\eta_i$.

Table 2

|    | + | - |
|----|---|---|
| $\eta_{LL}$ | 0.57 | 0.48 |
| $\eta_{LL}^3$ | 0.80 | 0.68 |
| $\eta_{RL}$ | 1.01 | 0.92 |
| $\eta_{LR}$ | 1.01 | 0.92 |

**Table Caption:** CCFR 95% C.L. limits on contact interactions. The signs + and - indicate the signs of $\eta_i$.
**Figure captions**

Fig. 1: Cross-section($Q^2 > Q^2_{\text{min}}$) is shown against minimum $Q^2$. The solid line corresponds to solution B and the dotted line corresponds to SM. The data points (combined H1 and ZEUS measurements) are shown for $Q^2 \geq 15000 GeV^2$.

Fig. 2: $y$ distribution is shown for $Q^2 > 15000 GeV^2$ for SM (dotted) and for solution B (solid).

Fig. 3: The Drell-Yan cross-section (for $|y| < 1, y$ is the rapidity) at the Tevatron is shown. The solid line corresponds to SM and the dotted line corresponds to the solution B.
Fig. 2

Fig. 3