Contact interactions and high-$Q^2$ events
in $e^+p$ collisions at HERA

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Abstract

We consider $eeqq$ contact interactions as a possible origin of an excess of events above Standard Model predictions in $e^+p \rightarrow e^+\text{jet}$ at high $Q^2$ observed by the H1 and ZEUS collaborations at HERA. The HERA data prefer chirality RL or LR contact terms and atomic physics parity violation measurements severely limit parity-odd contact terms. With equal left-right and right-left chirality interactions at an effective scale of order 3 TeV we are able to reproduce the main features of the HERA data and still be consistent with Drell-Yan pair production at the Tevatron and hadron production at LEP 2 and TRISTAN.
The H1 [1] and ZEUS [2] experiments at HERA have observed an excess of events in $e^+p \rightarrow e^+X$ at $Q^2 > 15,000$ GeV$^2$ compared to Standard Model (SM) expectations for deep inelastic scattering based on conventional structure functions [3 –5]. In terms of the kinematic variables $x = Q^2 / 2P \cdot q$ and $y = Q^2 / sx$ of deep inelastic scattering, the excess events occur at large $x$ and large $y$, $x > 0.25$ and $y > 0.25$. The final states of these events are clean, with a positron and a jet back-to-back in the transverse plane and essentially no missing transverse energy. Figure 1 shows the $x, y$ distribution of the events at $Q^2 > 10,000$ GeV$^2$ from the two experiments. Here the $x, y$ values from the ZEUS experiment are based on the double-angle method (to avoid uncertainties in the energy measurement); the H1 data are based on the energy and angle of the scattered positron. The event rate in the region $Q^2 > 15,000$ GeV$^2$ is about a factor of 2 above the SM prediction and corresponds to a cross section excess of about 0.4 pb.

There are several possibilities that might explain the observed excess. First, an upward statistical fluctuation could be responsible, although the probability for this at $Q^2 > 10,000$ GeV$^2$ is only 0.6% in the H1 experiment and 0.72% for $x > 0.55$ and $y > 0.25$ in the ZEUS experiment. A second possibility is that the parton densities at large $x$ are not well understood. However, it is largely the valence quark distributions which are relevant here and these are relatively well constrained in the high-$x$ region by BCDMS [6], NMC [7], SLAC [8] and CCFR [9] measurements. The ZEUS collaboration concludes that the uncertainty of this origin is only 6.5%. Another possibility is that large QCD effects occur near the edge of phase space. However, a very modest $K$-factor, $K \approx 1.1$ is found [10] over the entire high $Q^2$ $x$-$y$ range probed by the HERA experiments and thus there is no indication of large QCD logarithms needing summation. Since none of the above explanations seem particularly promising, it is natural to entertain new physics sources of the anomalous events.

The most obvious candidate for new physics is leptoquarks (LQ) or stops with $R$-parity violating couplings that are produced in the $s$-channel and which decay to $e^+$ and a quark [11–17]. An enhancement in the cross section would occur at a fixed $x$-value.
where \( \sqrt{s} \approx 300 \text{ GeV} \). The possibilities for \( e^+p \) production of leptoquarks or \( \tilde{R} \)-squarks are

\[
(i) \quad e^+u \rightarrow LQ^{5/3},
(ii) \quad e^+d \rightarrow \tilde{t}^{2/3},
(iii) \quad e^+\bar{u} \rightarrow \bar{D}^{1/3},
(iv) \quad e^+\bar{d} \rightarrow LQ^{4/3}
\]

Here \( \tilde{t} \) is the stop particle of supersymmetry and \( \bar{D} \) is the leptoquark state in the 27-dimensional representation of \( E_6 \). The cross-section for leptoquark production is

\[
\sigma(e^+p \rightarrow LQX) = \left(\frac{4\pi^2}{s}\right) f_{q/p}(x, M_{LQ}^2) \frac{\Gamma(LQ \rightarrow e^+q)}{M_{LQ}} (2J + 1),
\]

where \( f_{q/p} \) is the quark distribution in the proton and \( J \) is the spin of the leptoquark. From the excess in the \( e^+p \rightarrow e^+X \) cross section, \( \Delta \sigma \approx 0.4 \text{ pb} \), we can calculate the leptoquark decay width and estimate its coupling strength. For the above four scenarios, using MRSA structure functions and \( M_{LQ} = 200 \text{ GeV} \), we obtain for \( J = 0 \)

\[
\begin{array}{ccc}
(i) & 1.4 & 0.06 \\
(ii) & 5.7 & 0.12 \\
(iii) & 350 & 1.0 \\
(iv) & 130 & 0.6 \\
\end{array}
\]

where \( e = \sqrt{4\pi \alpha} \), \( \Gamma \) is the total leptoquark width and \( B \) is the branching fraction to the \( eq \) final state. Since the leptoquark width would be narrow, all of the excess events should fall in a single \( x \) bin, within resolution, in this \( s \)-channel resonance scenario. Although the H1 data above are somewhat suggestive of a resonant enhancement at \( M \approx 200 \text{ GeV} \) (see the vertical dotted line in Fig. 1), this interpretation is not indicated by the combined H1 and
ZEUS data. Of course, two or more leptoquark resonances could exist with similar but non-degenerate masses which could lead to a broader $x$-distribution. Since standard leptoquark and $R$-parity breaking [13,14] stop scenarios have been discussed extensively elsewhere, we do not pursue these interesting possibilities further here.

A final interesting potential explanation of the HERA high-$Q^2$ phenomena is new physics in the $t$-channel. Any particles beyond the photon and $Z$-boson that can be exchanged in the $t$-channel of $e^+p \to e^+X$ must have TeV mass scale to be consistent with present measurements of $e^+e^- \to q\bar{q}$ and $p\bar{p} \to e^+e^-X$. Thus models of this type can be generically parameterized by a contact interaction [17–20].

The conventional effective Lagrangian of an $eeqq$ contact interaction has the form [18–20]

$$L_{NC} = \sum_q \left[ \eta_{LL} \left( e_L^\gamma \gamma^\mu q_L \right) + \eta_{RR} \left( e_R^\gamma \gamma^\mu q_R \right) + \eta_{LR} \left( e_L^\gamma \gamma^\mu q_R \right) + \eta_{RL} \left( e_R^\gamma \gamma^\mu q_L \right) \right],$$

(8)

where the coefficients have dimension $(\text{TeV})^{-2}$ and are conventionally expressed as $\eta_{\alpha\beta}^{eq} = \epsilon 4\pi/\Lambda_{eq}^2$, where $\eta_{\alpha\beta}^{eq}$ and $\eta_{\alpha\beta}^{ed}$ are independent parameters. Here $\epsilon = \pm 1$ allows for either constructive or destructive interference with the SM $\gamma$ and $Z$ exchange amplitudes and $\Lambda_{eq}$ is the effective mass scale of the contact interaction. In the effective interaction (8) we do not include lepton or quark chirality violating terms such as $\overline{e_L} e_R^\alpha q_R^\beta$. This contact interaction can arise from particle exchanges in $s$, $t$, or $u$ channels for which the mass-squared of the exchanged particle is much larger than the corresponding Mandelstam invariant. A contact interaction may also be a manifestation of fermion compositeness [18]. Contact interactions which arise from the exchange of a single heavy particle will factorize into two vertex factors.

An example of a $t$-channel exchange is a heavy vector boson $Z'$, which gives

$$\eta_{\alpha\beta} = -g_\alpha^e g_\beta^q / M_{Z'}^2,$$

(9)

where $g_\alpha^e$ and $g_\beta^q$ are the $Z'$ couplings to $e_\alpha$ and $q_\beta$, respectively. In this case factorization implies additional contact interactions for $eeee$ and $qqqq$. If the interactions satisfy lepton universality there will be further contact amplitudes for $ee\mu\mu$, $ee\tau\tau$, etc. and, since couplings
to neutrinos are expected in general, $\nu\nuee$ and $\nu\nuqq$ contact interactions would also exist. There may also be corresponding contact interactions for charged currents such as $\nu\nuuu$ corresponding to heavy $W$-bosons. Thus a rich phenomenology could be associated with contact amplitudes representing new physics beyond the energy reach of present colliders.

The reduced amplitudes for $eq \to eq$, $\bar{q}q \to e^+e^-$, and $e^+e^- \to \bar{q}q$ subprocesses, including Standard Model plus contact interactions, are given by

$$M_{\alpha\beta}^{eq} = \frac{e^2 Q_e Q_q}{t} + \frac{g_Z^2 (T_{e\alpha}^3 - s_w^2 Q_e) (T_{q\beta}^3 - s_w^2 Q_q)}{t - m_Z^2} + \eta_{\alpha\beta}^{eq}, \quad (10)$$

where $Q_f$ and $T_{f\alpha}^3$ are charges and weak isospins, respectively, of the external fermions $f_\alpha$, $g_Z = e/(\sin \theta_w \cos \theta_w)$, $s_w = \sin \theta_w$, and the Mandelstam invariant $\hat{t}$ is given by

$$\hat{t} = (E_{\text{c.m.}})^2 \quad \text{for } e^+e^-, \quad \hat{t} = -Q^2 = -s xy \quad \text{for } e^+p, \quad \hat{t} = sx_1x_2 \quad \text{for } p\bar{p}. \quad (11)$$

Thus the presence of a contact interaction has interconnected implications for $ep \to eX$, $p\bar{p} \to e^+e^-X$, $e^+e^- \to$ hadrons and atomic physics parity violation experiments. The cross sections are related to the amplitudes (10) and parton densities $u$ and $d$ as follows:

$$\frac{d\sigma(e^+p)}{dx dy} = \frac{sx}{16\pi} \left\{ u(x, Q^2) \left[ |M_{LL}^u|^2 + |M_{RR}^u|^2 + (1-y)^2 \left( |M_{LL}^u|^2 + |M_{RR}^u|^2 \right) \right] 
+ d(x, Q^2) \left[ |M_{LL}^d|^2 + |M_{RR}^d|^2 + (1-y)^2 \left( |M_{LL}^d|^2 + |M_{RR}^d|^2 \right) \right] \right\} \quad (12)$$

$$\frac{d\sigma(e^-p)}{dx dy} = \frac{sx}{16\pi} \left\{ u(x, Q^2) \left[ |M_{LL}^u|^2 + |M_{RR}^u|^2 + (1-y)^2 \left( |M_{LL}^u|^2 + |M_{RR}^u|^2 \right) \right] 
+ d(x, Q^2) \left[ |M_{LL}^d|^2 + |M_{RR}^d|^2 + (1-y)^2 \left( |M_{LL}^d|^2 + |M_{RR}^d|^2 \right) \right] \right\} \quad (13)$$

$$\frac{d\sigma(p\bar{p} \to \ell\bar{\ell}X)}{dx_1 dx_2 d\cos \theta} = \frac{\hat{s}}{384\pi} \left\{ (1 + \cos \hat{\theta})^2 \left[ u(x_1, \hat{s})u(x_2, \hat{s}) \left( |M_{LL}^u|^2 + |M_{RR}^u|^2 \right) 
+ d(x_1, \hat{s})d(x_2, \hat{s}) \left( |M_{LL}^d|^2 + |M_{RR}^d|^2 \right) \right] 
+ (1 - \cos \hat{\theta})^2 \left[ u(x_1, \hat{s})u(x_2, \hat{s}) \left( |M_{LL}^u|^2 + |M_{RR}^u|^2 \right) 
+ d(x_1, \hat{s})d(x_2, \hat{s}) \left( |M_{LL}^d|^2 + |M_{RR}^d|^2 \right) \right] \right\} \quad (14)$$
\[
\frac{d\sigma(e^+e^- \to q\bar{q})}{d\cos \theta} = \frac{3s}{128\pi} \sum_q \left\{ (1 + \cos \theta)^2 \left( |M_{LL}^{eq}|^2 + |M_{RR}^{eq}|^2 \right) + (1 - \cos \theta)^2 \left( |M_{LR}^{eq}|^2 + |M_{RL}^{eq}|^2 \right) \right\}.
\]

(15)

A parity non-conserving contact interaction would modify the SM prediction for the atomic physics parity violating parameter \(Q_W\), given by

\[
Q_W = Q_{W}^{\text{SM}} - \frac{1}{\sqrt{2G_F}} \left[ (N + 2Z)\Delta \eta^{eu} + (2N + Z)\Delta \eta^{ed} \right],
\]

(16)

where \(N\) is the number of neutrons, \(Z\) is the number of protons, and

\[
\Delta \eta^{eq} = \eta^{eq}_{RR} - \eta^{eq}_{LL} + \eta^{eq}_{RL} - \eta^{eq}_{LR}.
\]

(17)

The \(^{133}\)Cs measurements find \(Q_W = -71.04 \pm 1.81\) while the SM prediction for \(m_t = 175\) GeV and \(m_H = 100\) GeV is \(Q_{W}^{\text{SM}} = -73.04\). The difference \(\Delta Q_W = 2.0 \pm 1.8\) places a severe constraint on allowable contact interactions,

\[
\Delta Q_W = (11.4 \text{ TeV}^2) \left( \eta^{eu}_{LL} + \eta^{eu}_{LR} - \eta^{eu}_{RL} - \eta^{eu}_{RR} \right) + (12.8 \text{ TeV}^2) \left( \eta^{ed}_{LL} + \eta^{ed}_{LR} - \eta^{ed}_{RL} - \eta^{ed}_{RR} \right).
\]

(18)

Parity conserving contact interactions such as \(\eta^{eq}_{LR} = \eta^{eq}_{RL}\) and \(\eta^{eq}_{LL} = \eta^{eq}_{RR}\) give \(\Delta Q_W = 0\).

In order to develop some feeling for the interference of the SM and contact amplitudes, we give numerical values for the SM chirality amplitudes in Table I at relevant values of \(\hat{t}\), namely \(\hat{t} = -20,000\) GeV\(^2\) for \(eq \to eq\) and \(\hat{t} = (175\) GeV\(^2\) for \(\bar{q}q \to e^+e^-\) or \(e^+e^- \to q\bar{q}\). The SM amplitude changes sign under crossing, because \(1/\hat{t}\) changes sign in the dominant photon amplitude, but the contact terms have the same sign in both direct and crossed channel amplitudes. This has the consequence that constructive interference in an \(eq \to eq\) amplitude corresponds with destructive interference in the \(q\bar{q} \to e^+e^-\) amplitude. Moreover, \(ep\) cross sections may be more or less sensitive to the presence of the contact amplitude than \(e^+e^-\) or \(\bar{p}p\), depending on the relative size of the SM contributions and the sign of the contact contribution.

From (12) we see that a high-\(y\) anomaly in \(e^+p\) requires an \(\eta^{eq}_{LR}\) or \(\eta^{eq}_{RL}\) amplitude that interferes constructively with the SM contribution. \(\eta^{eq}_{LL}\) or \(\eta^{eq}_{RR}\) amplitudes are suppressed.
TABLE I. Chirality amplitudes for $e^- q \rightarrow e^- q$ at $\hat{t} = -20,000 \text{ GeV}^2$ and for $\bar{q} q \rightarrow e^+ e^-$ or $e^+ e^- \rightarrow \bar{q} q$ at $\hat{t} = (175 \text{ GeV})^2$, where $q = u, d$. The amplitude units are $(\text{TeV})^{-2}$.

|     | $eu \rightarrow eu$ | $cd \rightarrow ed$ | $\bar{u}u \rightarrow e^+ e^-$ | $\bar{d}d \rightarrow e^+ e^-$ |
|-----|----------------------|----------------------|-----------------------------|-----------------------------|
| $LL$ | $5.1 + \eta_{LL}^{eu}$ | $-3.8 + \eta_{LL}^{ed}$ | $-4.4 + \eta_{LL}^{eu}$ | $3.9 + \eta_{LL}^{ed}$ |
| $RR$ | $3.9 + \eta_{RR}^{eu}$ | $-2.0 + \eta_{RR}^{ed}$ | $-3.0 + \eta_{RR}^{eu}$ | $1.5 + \eta_{RR}^{ed}$ |
| $LR$ | $2.4 + \eta_{LR}^{eu}$ | $-1.2 + \eta_{LR}^{ed}$ | $-1.1 + \eta_{LR}^{eu}$ | $0.6 + \eta_{LR}^{ed}$ |
| $RL$ | $1.7 + \eta_{RL}^{eu}$ | $0.3 + \eta_{RL}^{ed}$ | $-0.2 + \eta_{RL}^{eu}$ | $-1.3 + \eta_{RL}^{ed}$ |

by the $(1 - y)^2$ factor in $e^+ p$ collisions but would be enhanced compared to $\eta_{LR}$ or $\eta_{RL}$ terms in $e^- p$ scattering. Because the $d$-parton density is severely suppressed in the large $x$ region relative to the $u$-parton density [3–5], the $eu$ contact interaction is needed to achieve an $e^+ p$ cross section enhancement. As an illustrations we consider the following scenarios for the contact contributions:

\[
\eta_{RL}^{eu} = \eta_{LR}^{eu} = 1.4 \text{ TeV}^{-2}, \tag{19}
\]
\[
\eta_{RL}^{eu} = -\eta_{LR}^{eu} = 2.6 \text{ TeV}^{-2}. \tag{20}
\]

These correspond to effective scales $\Lambda_{eu} = 3 \text{ TeV}$ and $\Lambda_{eu} = 2.2 \text{ TeV}$, respectively.

The effect on the HERA cross sections is demonstrated in Figs. 2 and 3. In Fig. 2 we show the $e^+ p$ DIS cross section, $\sigma(Q^2 > Q_{\text{min}}^2)$, as a function of the minimal $Q^2$ value; also included are the HERA results from Refs. [1,2], corrected for detection efficiencies of 80% and 81.5%, respectively, and divided by an average QCD K-factor of 1.1 since we are showing leading order cross sections throughout. Both choices give better representations of the data than the SM at $Q^2 > 15,000 \text{ GeV}^2$. The second scenario was chosen to introduce a destructive interference with SM amplitudes at $Q_{\text{min}}^2 \approx 10,000 \text{ GeV}^2$. The corresponding SM and contact interaction contributions to $d\sigma/dx$ and $d\sigma/dy$ for $e^+ p \rightarrow e^+ X$ are shown in Figure 3. The features of the data in Fig. 1 are qualitatively reproduced by these choices of contact terms.
Of the two scenarios, the first case is parity conserving, with a $VV - AA$ interaction in (19), where $V$ denotes vector and $A$ axial vector, and thus satisfies the $Q_W$-constraint. The choice in (20) improves the description of the HERA $Q^2$ distribution over (19) but it gives a contribution $\Delta Q_W(\text{contact}) = -59.3$ that is in severe conflict with the measured value. This $Q_W$-discrepancy can be rectified by introducing additional, cancelling $\eta^u_{LL}$ or $\eta^u_{RR}$ contributions or contact terms involving $d$-quarks. Such a change would affect the HERA $e^+p$ cross sections very little, due to the $(1 - y)^2$ terms in Eq. (12) and the suppressed down-quark density.

Figure 4 compares the SM prediction for the Drell-Yan cross section at the Tevatron with the calculated cross section for the contact amplitudes of (19) and (20). We see that the contact amplitudes in (19) are consistent with the preliminary CDF [21] data but the choice in (20) is ruled out. Any attempt to resolve the $Q_W$-discrepancy of scenario (20) by additional contact terms will further worsen the disagreement with the CDF data. The changes in $\sigma(e^+e^- \rightarrow \text{hadrons})$ caused by (19) and (20) are sufficiently small as not to conflict with current LEP 2 measurements [17,22].

In summary we have demonstrated the following:

1. The presence of an $eeuu$ contact term could satisfactorily explain the observed excess of events at high $Q^2$ in the HERA H1 and ZEUS experiments.

2. A new physics scale $\Lambda \lesssim 3$ TeV in LR and/or RL amplitudes is required.

3. The CDF Drell-Yan data allow a contact term of this order, as long as it occurs in only one or two of the eight chirality amplitudes for $u\bar{u} \rightarrow e^+e^-$ and $d\bar{d} \rightarrow e^+e^-$. 

4. A destructive interference would cause a rapid onset of the new physics contributions with increasing $Q^2$ which would improve the agreement with the shape of the $Q^2$ distribution at HERA. However, because of the tightness of the Tevatron bounds on $eeqq$ contact terms there is little room to tolerate such destructive interference.
5. Atomic physics parity violation measurements severely constrain parity-odd contact terms.

6. Deeply inelastic $e^- p$ scattering is not sensitive to the LR and RL terms needed to explain the $e^+ p$ data but would be complementary in probing LL and RR contact terms. However, the presence of additional chirality terms would exacerbate the situation with the Drell-Yan cross section at high lepton-pair mass.

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FIGURE CAPTIONS

Fig. 1: Event distributions at $Q^2 > 10,000$ GeV$^2$ in $e^+p \rightarrow e^+X$ from the H1 (solid points) and ZEUS (open points) experiments.

Fig. 2: Integrated cross sections versus a minimum $Q^2$ for $e^+p \rightarrow e^+X$ for the SM (solid curve) and the contact interactions of (19) (dashed curve) and (20) (dotted curve). The data points are combined H1 and ZEUS measurements.

Fig. 3: Predicted $x$ and $y$ distributions for $Q^2 > 15,000$ GeV$^2$ and $y > 0.2$ for the SM (solid curves) and with two choices of the contact interactions of (19) (dashed curves) and (20) (dotted curves).

Fig. 4: The Drell-Yan cross section $\bar{p}p \rightarrow \mu^+\mu^-X + e^+e^-X$ at the Tevatron ($\sqrt{s} = 1.8$ TeV) for the SM with the contact interactions of (19) (dashed curve) and (20) (dotted curve). Preliminary CDF data from Ref. [21] are compared. A constant $K$-factor is determined from the data in the region of the $Z$-resonance.
Fig. 3
$d^2\sigma/dM dy$ for $|y|<1$ (pb/GeV)