Contact Interactions: Results from ZEUS and a Global Analysis

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In a search for signatures of physics processes beyond the Standard Model, various eeqq vector contact interaction hypotheses have been tested in the ZEUS experiment. No significant evidence of a contact interaction signal has been found. The analysis is based on NC $e^+p$ DIS data corresponding to an integrated luminosity of $47.7 \text{ pb}^{-1}$ and results in 95% CL limits on the effective mass scales $\Lambda$ ranging from 1.7 to 5 TeV for the different one-parameter contact interaction scenarios considered.

Within the global analysis, including data from other experiments as well, any contact interactions with mass scale below 2.1 TeV are excluded at 95% CL. Combined mass scale limits for specific one-parameter scenarios range from 5.1 to 18 TeV. Upper limits on possible effects to be observed in future HERA, LEP and Tevatron running are estimated. The total hadronic cross-section at LEP and $e^-p$ scattering cross-section at HERA are strongly constrained by existing data, whereas large cross-section deviations are still possible for Drell-Yan lepton pair production at the Tevatron.

1. INTRODUCTION

The HERA $ep$ collider has extended the kinematic range available for the study of deep-inelastic scattering (DIS) by two orders of magnitude to values of $Q^2$ up to about 50000 GeV$^2$. Measurements in this domain allow new searches for physics processes beyond the Standard Model (SM) at characteristic mass scales in the TeV range. The recent analyses were stimulated in part by an excess of events over the SM expectation for $Q^2 > 20000 \text{ GeV}^2$ reported in 1997 by the ZEUS [1] and H1 [2] collaborations, for which electron-quark contact interactions (CI) have been suggested as possible explanations.

2. CONTACT INTERACTIONS

Four-fermion contact interactions are an effective theory, which allows us to describe, in the most general way, possible low energy effects coming from "new physics" at much higher energy scales. This includes the possible existence of second-generation heavy weak bosons, leptoquarks as well as electron and quark compositeness [3,4]. As strong limits beyond the HERA sensitivity have already been placed on the scalar and tensor terms [4], only the vector eeqq contact interactions are considered in this study. They can be represented as additional term in the Standard Model Lagrangian [4]:

$$L_{CI} = \frac{g^2}{\Lambda^2} \sum_{i,j=L,R} \eta^{ij}_{\ell q} (\bar{\ell}_i \gamma^\mu \ell_i) (\bar{q}_j \gamma^\mu q_j)$$

(1)

where the sum runs over electron and quark helicities, $\epsilon$ is the overall sign of the CI Lagrangian, $g$ is the coupling, and $\Lambda$ is the effective mass scale. Helicity and flavour structure of contact interactions is described by set of parameters $\eta^{ij}_{\ell q}$. Since $g$ and $\Lambda$ always enter in the combination $g^2/\Lambda^2$, we fix the coupling by adopting the convention $g^2 = 4\pi$. In the ZEUS analysis 30 specific CI scenarios are considered. Assumed relations between different couplings are listed in Table 1. Each line in the table represents two scenarios, one for $\epsilon = +1$ and one for $\epsilon = -1$. For the models VV, AA, VA and X1 to X6 all quark flavours are assumed to have the same contact interaction couplings and each of the $\eta^{ij}_{\ell q}$ is either zero or $\pm 1$. For the U1 to U6 models only couplings of up-type quarks ($u$ and $c$) are considered.

The global analysis combining data from different experiments (see sections 4 and 5) also takes into account three less constrained models, in which different couplings can vary independently. The General Model assumes that contact interactions couple only electrons to $u$ and
Table 1
Coupling structure and the 95% CL limits on the effective mass scales for different one-parameter contact interaction models. Results from the ZEUS analysis based on high-$Q^2$ $e^+p$ NC DIS data are compared to results based on the combined electron/muon NC data (global analysis not assuming SU(2) invariance) and those corresponding to all available data (global analysis with SU(2) universality).

<table>
<thead>
<tr>
<th>Model</th>
<th>Couplings</th>
<th>$e^+p$ NC DIS data</th>
<th>$e/\mu$ NC data</th>
<th>All data</th>
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<tbody>
<tr>
<td>VV</td>
<td>+ + + +</td>
<td>$\Lambda_{\text{min}}$ [TeV]</td>
<td>$\Lambda_{\text{min}}$ [TeV]</td>
<td>$\Lambda_{\text{min}}$ [TeV]</td>
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<tr>
<td>AA</td>
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<td>9.8</td>
<td>10.7</td>
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<tr>
<td>VA</td>
<td>+ - + -</td>
<td>2.6</td>
<td>10.5</td>
<td>10.1</td>
</tr>
<tr>
<td>X1</td>
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<td>6.6</td>
<td>6.2</td>
</tr>
<tr>
<td>X2</td>
<td>+ + +</td>
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<td>8.7</td>
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</tr>
<tr>
<td>X4</td>
<td>+ + +</td>
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<td>9.9</td>
<td>10.2</td>
</tr>
<tr>
<td>X5</td>
<td>+ + +</td>
<td>3.3</td>
<td>5.7</td>
<td>5.2</td>
</tr>
<tr>
<td>X6</td>
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<td>6.2</td>
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</tr>
<tr>
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<td>+ - -</td>
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<td>6.4</td>
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<td>U2</td>
<td>+ + -</td>
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<td>U4</td>
<td>+ + +</td>
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<td>U5</td>
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<tr>
<td>U6</td>
<td>+ - -</td>
<td>1.8</td>
<td>7.0</td>
<td>5.6</td>
</tr>
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</table>

3. ZEUS ANALYSIS

The ZEUS analysis compares the distributions of the measured kinematic variables with the corresponding distributions from a MC simulation of $e^+p \rightarrow e^+X$ events reweighted to simulate the CI scenarios. An unbinned log-likelihood technique is used to calculate $L(\epsilon/\Lambda^2)$ from the individual kinematic event coordinates $(x_i, y_i)$:

$$L(\epsilon/\Lambda^2) = - \sum_{i\in\text{data}} \log p(x_i, y_i; \epsilon/\Lambda^2),$$

where the sum runs over all events in the selected data sample and $p(x_i, y_i; \epsilon/\Lambda^2)$ is the probability corresponding to the direct “new physics” contribution, is expected for most CI scenarios, as shown in Figure 1. At intermediate $Q^2$ a moderate increase or decrease due to CI-SM interference terms is possible. As the helicity structure of new interactions can be different from that of the Standard Model, also the differential cross-section $d\sigma/dx$ (for fixed $Q^2$) is modified. Sensitivity to many CI scenarios is significantly improved by considering the two-dimensional event distribution.
that an event $i$ observed at $(x_i, y_i)$ results from the model described by coupling $\epsilon/\Lambda^2$. $L$ tests the shape of the $(x, y)$-distribution but is independent of its absolute normalisation.

The best estimates, $\Lambda_{\pm}^{\sigma}$, for the different CI scenarios are given by the positions of the respective minima of $L(\epsilon/\Lambda^2)$ for $\epsilon=\pm1$. All results are consistent with the Standard Model, the probability that the observed values of $\Lambda_{\pm}^{\sigma}$ result from the Standard Model does not fall below 16%. The 95% C.L. lower limits $\Lambda_{\min}$ on the effective mass scale $\Lambda$ are defined as the mass scales for which MC experiments have a 95% chance to result in $\Lambda_{\pm}$ values smaller than that observed in data. The lower limits on $\Lambda$ ($\Lambda_{\min}^{\pm}$ for $\epsilon=\pm1$) are summarized in Table 1. The $\Lambda$ limits range from 1.7 to 5 TeV.

4. GLOBAL ANALYSIS

The global analysis [8] of $eeqq$ contact interactions combines relevant data from different experiments: ZEUS and H1 high-$Q^2$ NC DIS results; Tevatron data on high-mass Drell-Yan lepton pair production; LEP2 results on the hadronic cross-section $\sigma(e^+e^- \rightarrow q\bar{q}(\gamma))$, the heavy quark production ratios $R_b$ and $R_c$, and the forward-backward asymmetries $A_{FB}^b$, $A_{FB}^c$, $A_{FB}^{q\bar{q}}$: data from low-energy $eN$ and $\mu N$ scattering and from atomic parity violation (APV) measurements.

For models assuming $SU(2)_L \times U(1)_Y$ universality, additional constraints come from HERA $e^+p$ CC DIS results, data on $\nu N$ scattering, universality of the CKM matrix and electron-muon universality.

The combined data are consistent with the Standard Model predictions. The mass scale limits $\Lambda_{\min}^e$ and $\Lambda_{\min}^\nu$ obtained from fitting one-parameter models to all available data are summarized in Table 1. For models not assuming $SU(2)_L \times U(1)_Y$ universality (only $e/\mu$ NC data used) the mass limits range from 5.1 to 11.7 TeV. With $SU(2)_L \times U(1)_Y$ universality (using also $\nu N$ and CC data) the limits extend up to about 18 TeV.

Limits for single couplings derived in multi-parameter models (of Section 2) are weaker than in the case of one-parameter models, as no relation between separate couplings is assumed. The mass limits obtained for the general model range from 2.1 to 5.1 TeV. All limits improve significantly and reach 3.5 to 7.8 TeV for the SU(2) model with family universality.

Taking into account possible correlations between couplings, any contact interaction with a mass scale below 2.1 TeV (3.1 TeV when SU(2) universality is assumed) is excluded at 95% CL.

5. PREDICTIONS

Likelihood function for the possible cross-section deviations from the Standard Model predictions is calculated as the weighted average over all contributing CI coupling combinations [8]. The results for HERA, in terms of the 95% C.L. limit bands on the ratio of predicted and the Standard Model cross-section deviations from the Standard Model predictions. The mass scale limits obtained for the general model range from $2.1$ to $5.1$ TeV. All limits improve significantly and reach $3.5$ to $7.8$ TeV for the SU(2) model with family universality.

The allowed increase in the integrated $e^+p$ NC DIS cross-section for $Q^2 > 15,000$ GeV$^2$ is about 40% for the general model and about 30% for the SU(2) model. In order to reach the level of statistical precision which would allow to confirm a possible discrepancy of this size, the HERA experiments would have to collect $e^+p$ integrated luminosities of the order of $100-200$ pb$^{-1}$ (depending on the model). This will be possible after the HERA upgrade planned for year 2000.

Constraints on possible deviations from the Standard Model predictions are much stronger in
Figure 2. The 95% CL limit band on the ratio of predicted to the Standard Model cross-section for $e^+p$ and $e^-p$ NC DIS scattering at HERA.

Figure 3. The 68% and 95% CL contours for the possible deviation from the Standard Model predictions, for $e^+p$ NC DIS cross-section at H1, at $Q^2 = 30,000 \text{ GeV}^2$, total $e^+e^- \rightarrow q\bar{q}$ cross-section at $\sqrt{s} = 400 \text{ GeV}$ and Drell-Yan lepton pair production cross-section at the Tevatron, at $M_{t\bar{t}} = 500 \text{ GeV}$, as indicated on the plot. The limits are calculated using the SU(2) contact interaction model with family universality.

as constraints resulting from different processes are, to large extent, complementary.

REFERENCES
   R.Pawlak, ZEUS High $Q^2$ $e^+p$ and $e^-p$ Cross Sections, these proceedings.