Search for Contact Interactions at HERA

- General Compositeness
- Heavy Leptoquarks
- Large Extra Dimensions
- Quark Radius

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Kinematic Range

HERA accesses large reach in kinematic plane
High mass states produced at large $Q^2$
Sensitive to 4-fermion contact interactions
Look at $Q^2$ dependence of DIS cross section...
Deep Inelastic Scattering

\[
\frac{d\sigma_{\text{NC}}^{\pm}}{dx dQ^2} = \frac{2\pi\alpha^2}{x} \left[ \frac{1}{Q^2} \right]^2 \left[ Y_+ \tilde{F}_2 + Y_- x\tilde{F}_3 - y^2 \tilde{F}_L \right]
\]

\[
\frac{d\sigma_{\text{CC}}^{\pm}}{dx dQ^2} = \frac{G_F^2}{4\pi x} \left[ \frac{M_W^2}{M_W^2 + Q^2} \right]^2 \left[ Y_+ \tilde{W}_2^\pm + Y_- x\tilde{W}_3^\pm - y^2 \tilde{W}_L^\pm \right]
\]

\[ Y_\pm = 1 \pm (1 - y)^2 \]

\[
\tilde{F}_2 \propto \sum (xq_i + x\bar{q}_i)
\]

Dominant contribution

\[
x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)
\]

Only sensitive at high \( Q^2 \sim M_Z^2 \)

\[
\tilde{F}_L \propto \alpha_s \cdot xg(x, Q^2)
\]

Only sensitive at low \( Q^2 \) and high \( y \)

Weak dependence from QCD part of SM

Dominant \( Q^2 \) dependence from electroweak part of SM

Similarly for pure weak CC analogues:

\( W_2^\pm, xW_3^\pm \) and \( W_L^\pm \)
Neutral and charged current processes measured across wide $Q^2$ range

Full HERA data set used
Neutral current event selection:

High $P_T$ isolated scattered lepton
Suppress huge photo-production background by imposing longitudinal energy-momentum conservation

Kinematics may be reconstructed in many ways:
energy/angle of hadrons & scattered lepton provides excellent tools for sys cross checks

Removal of scattered lepton provides a high stats “pseudo-charged current sample”
Excellent tool to cross check CC analysis

Final selection: $\sim 10^5$ events per sample at high $Q^2$
$\sim 10^7$ events for $10 < Q^2 < 100$ GeV$^2$
**HERA Operation**

**HERA-I operation 1993-2000**
- Ee = 27.6 GeV
- Ep = 820 / 920 GeV
- \( \int L \sim 110 \text{ pb}^{-1} \) per experiment

**HERA-II operation 2003-2007**
- Ee = 27.6 GeV
- Ep = 920 GeV
- \( \int L \sim 330 \text{ pb}^{-1} \) per experiment

Longitudinally polarised leptons

**Low Energy Run 2007**
- Ee = 27.6 GeV
- Ep = 575 & 460 GeV
- Dedicated \( F_L \) measurement

**Total luminosity presented here = 446 pb\(^{-1}\)**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>( L_{\text{int}} ) [pb(^{-1})]</th>
<th>( \sqrt{s} ) [GeV]</th>
<th>Polarisation (( P_e ) [%])</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^+p \rightarrow e^+X )</td>
<td>36</td>
<td>301</td>
<td>Unpolarised</td>
</tr>
<tr>
<td>( e^-p \rightarrow e^-X )</td>
<td>16</td>
<td>319</td>
<td>Unpolarised</td>
</tr>
<tr>
<td>( e^+p \rightarrow e^+X )</td>
<td>65</td>
<td>319</td>
<td>Unpolarised</td>
</tr>
<tr>
<td>( e^-p \rightarrow e^-X )</td>
<td>46</td>
<td>319</td>
<td>Right (( P_e = +37 ))</td>
</tr>
<tr>
<td>( e^-p \rightarrow e^-X )</td>
<td>103</td>
<td>319</td>
<td>Left (( P_e = -26 ))</td>
</tr>
<tr>
<td>( e^+p \rightarrow e^+X )</td>
<td>98</td>
<td>319</td>
<td>Right (( P_e = +33 ))</td>
</tr>
<tr>
<td>( e^+p \rightarrow e^+X )</td>
<td>82</td>
<td>319</td>
<td>Left (( P_e = -38 ))</td>
</tr>
</tbody>
</table>

Status: 1-July-2007
\[ \chi^2(\eta, \varepsilon) = \sum_i \frac{\left( \sigma_i^{\text{exp}} - \sigma_i^{\text{th}}(\eta) \left( 1 - \sum_k \Delta_{ik}(\varepsilon_k) \right) \right)^2}{\delta_i^{\text{stat}} \sigma_i^{\text{exp}} \sigma_i^{\text{th}}(\eta) \left( 1 - \sum_k \Delta_{ik}(\varepsilon_k) \right) + (\delta_{i,\text{uncor}} \sigma_i^{\text{exp}})^2} + \sum_k \varepsilon_k^2 \]

A selection of new physics models are tested.
Minimise \( \chi^2 \) function w.r.t. model parameters \( \eta \)
Take into account systematic uncertainties on measurements \( \Delta_{ik} \) for each error source \( \varepsilon_k \)

PDFs taken from CTEQ6m
Unbiased PDFs - constrained by:

\( \chi^2/\text{ndf} (\eta=0) = 16.4/17 \) for \( e^+p \)
\( 7.0/16 \) for \( e^-p \)

insensitive to eq contact interactions

Alternative H1PDF2009 also used as check

\[ \text{arXiv:0904.0929} \]
Include additional term to SM lagrangian

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{CI} \]

\[ \mathcal{L}_{CI} = \sum_{i,j=L,R} \eta_{ij}^{eq} \left( \bar{e}_i \gamma_\mu e_i \right) \left( \bar{q}_j \gamma^\mu q_j \right) \]

\[ \eta_{L,R}^{eq} = \frac{\pm 4\pi}{\Lambda^2} \]

Several general models tested
Single common compositeness scale \( \Lambda \)
Different L,R fermion helicities
Different Vector / Axial-vector chiral couplings

Different models will interfere constructively or destructively with SM
Search For General Compositeness

Lower limits at 95% CL on effective mass scale: $\Lambda > 3.2$ to 7.2 TeV

<table>
<thead>
<tr>
<th>Chiral Model</th>
<th>$\Lambda^-$ [TeV]</th>
<th>$\Lambda^+$ [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL</td>
<td>4.0</td>
<td>4.2</td>
</tr>
<tr>
<td>LR</td>
<td>3.7</td>
<td>4.8</td>
</tr>
<tr>
<td>RL</td>
<td>3.8</td>
<td>4.8</td>
</tr>
<tr>
<td>RR</td>
<td>3.9</td>
<td>4.4</td>
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<tr>
<td>VV</td>
<td>7.2</td>
<td>5.6</td>
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<tr>
<td>AA</td>
<td>5.1</td>
<td>4.4</td>
</tr>
<tr>
<td>VA</td>
<td>3.6</td>
<td>3.8</td>
</tr>
<tr>
<td>LL+RR</td>
<td>5.1</td>
<td>5.3</td>
</tr>
<tr>
<td>LR+RL</td>
<td>4.8</td>
<td>5.4</td>
</tr>
</tbody>
</table>
Search for heavy leptoquarks

Lower limits at 95% CL:
$M_{LQ}/\lambda > 0.41$ to 1.86 TeV

Search for lepto-quarks with masses $M_{LQ} \gg \sqrt{s}$ produced with coupling $\lambda$

Search for scalar and vector LQs with:
- L and R chirality
- fermion number $F=0$ or 2

$\eta = \epsilon \frac{\lambda^2}{M^2_{LQ}}$

$\epsilon = 0, \pm \frac{1}{2}, \pm 1, \pm 2$
## Search for Heavy Leptoquarks

### Lower limits at 95% CL:
$M_{LQ}/\lambda > 0.41$ to 1.86 TeV

<table>
<thead>
<tr>
<th>LQ</th>
<th>$\eta^q_{ab} = \epsilon^q_{ab} \frac{\lambda^2}{M_{LQ}^2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S^L_0$</td>
<td>$\epsilon^u_{LL} = +\frac{1}{2}$</td>
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<tr>
<td></td>
<td>$\epsilon^d_{ab}$</td>
</tr>
<tr>
<td></td>
<td>$F$</td>
</tr>
<tr>
<td></td>
<td>$M_{LQ}/\lambda$ [TeV]</td>
</tr>
<tr>
<td>$S^R_0$</td>
<td>$\epsilon^u_{RR} = +\frac{1}{2}$</td>
</tr>
<tr>
<td>$\tilde{S}^R_0$</td>
<td>$\epsilon^d_{RR} = +\frac{1}{2}$</td>
</tr>
<tr>
<td>$S^{1/2}_0$</td>
<td>$\epsilon^u_{LR} = -\frac{1}{2}$</td>
</tr>
<tr>
<td></td>
<td>$\epsilon^d_{RL} = -\frac{1}{2}$</td>
</tr>
<tr>
<td>$S^L_{1/2}$</td>
<td>$\epsilon^u_{RL} = -\frac{1}{2}$</td>
</tr>
<tr>
<td></td>
<td>$\epsilon^d_{LR} = -\frac{1}{2}$</td>
</tr>
<tr>
<td>$S^L_1$</td>
<td>$\epsilon^u_{LL} = +\frac{1}{2}$</td>
</tr>
<tr>
<td></td>
<td>$\epsilon^d_{LL} = +1$</td>
</tr>
</tbody>
</table>

Search for lepto-quarks with masses $M_{LQ} \gg \sqrt{s}$ produced with coupling $\lambda$

Search for scalar and vector LQs with:
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$$\eta = \epsilon \frac{\lambda^2}{M_{LQ}^2}$$

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Search For Large Extra Dimensions

Compactified extra dimensions of size $R$ could become accessible at high energies below Planck scale $M_P$. New gravity scale in $n$ extra dimensions is $M_S$

$$M_S^{2+n} = \frac{M_P^2}{R^n}$$

coupling $\eta_G = \frac{\lambda}{M_S^4}$

with $\lambda = \pm 1$
Search for quark sub-structure
Assume point-like electron
Simple form-factor model for the mean squared radius of electroweak charge on the quark $\langle R^2 \rangle$

$$f(Q^2) = 1 - \frac{\langle R^2 \rangle}{6} Q^2$$

**Upper limit at 95% CL**
$R < 0.65 \times 10^{-18}$ m
Conclusions

A range of new phenomena models are explored
New limits on compositeness models factor ~2 higher than previous H1 measurements
Comparable limits to LEP and Tevatron