Search for Leptoquarks and Contact Interactions at HERA

Robert Ciesielski on behalf of H1 and ZEUS Collaborations
HERA operation

World's only ep collider, located at DESY Hamburg. Ended in June 2007, after 15 years of successful running. Two colliding experiments: H1 and ZEUS.

\[ p (820/920 \text{ GeV}) \quad \text{and} \quad e (27.5 \text{ GeV}) \]
\[ \sqrt{s} = 318 \text{ GeV} \]

HERA I (1994-2000)
\[ L=\sim 120 \text{ pb}^{-1} \text{ collected per experiment. Mostly } e^+p. \]

HERA II (2002-2007)
\[ L=\sim 360 \text{ pb}^{-1} \text{ collected per experiment. Similar amount of } e^+p \text{ and } e^-p. \]
Longitudinal polarisation of lepton beam (P=0.3-0.4).

Presented results are based on full datasets (almost 0.5 fb\(^{-1}\) per experiment).
High-$Q^2$ NC and CC Cross Sections

Main processes studies at HERA:
- Neutral Current (NC) DIS, $e p \rightarrow e X$, mediated by $\gamma$ or $Z^0$.
- Charged Current (CC) DIS, $e p \rightarrow \nu X$, mediated by $W^\pm$.

Excellent agreement between data and SM predictions over many orders of magnitude. Precise tests of QCD and EW physics.

$Q^2$ (resolving power) up to 40000 GeV$^2$.
Spatial resolution $\sim 1/Q \approx 10^{-18}$ m $= 10^{-3}$ fm.
1/1000 of proton radius.

Search for Beyond SM physics performed by looking for possible deviations at highest $Q^2$:
- Contact Interactions (NC)
- Leptoquark production (NC, CC)
Quark Radius

Quark form-factor (electron assumed to be point-like).
If a quark has a finite size, the SM cross section is expected to decrease at higher $Q^2$:

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \left[ 1 - \frac{R_q^2}{6Q^2} \right]^2$$

$R_q$ is a root-mean-square radius of the EW charge distribution in the quark.
The same dependence expected for $e^p$ and $e^+p$.

Excellent agreement with SM expectations up to highest $Q^2$.

ZEUS (94-07 data): $R_q < 0.63 \times 10^{-3}$ fm
H1 (94-07 data): $R_q < 0.74 \times 10^{-3}$ fm

@ 95% C.L.
Large Extra Dimensions

Arkani-Hamed-Dimopolous-Dvali Model

If gravity propagates in 4+δ dimensions, effective Plank scale $M_S$ can be as low as 1 TeV. Gravity becomes comparable in strength to electroweak interactions.

Contribution of graviton exchange (Kaluza-Klein tower) to $e^\pm p$ NC DIS can be described by effective coupling:

$$\eta_G = \lambda \frac{\epsilon^2}{M_S^4}$$

where $\lambda = \pm 1$ is the coupling strength and $\epsilon$ is related to the energy scale of hard interaction.

ZEUS (94-07 data): $M_S^+ > 0.94$ TeV, $M_S^- > 0.94$ TeV (95% C.L.)
Contact Interactions (CI)

New interactions at higher scale ($\Lambda \gg \sqrt{s}$) can be effectively described at lower energies as 4-fermion $eeqq$ Contact Interactions (CI).

Reminder: before $W$ and $Z^0$ were discovered, weak interactions ($\Lambda \approx M_w$) were described as 4-fermion CI with Fermi constant $G_F = g^2/M^2_w$.

At HERA:

\[
M^e_{\alpha\beta}(Q^2) = \frac{e^2 e_q}{Q^2} - \frac{e^2}{\sin^2\theta_W \cos^2\theta_W} \frac{g^e_{\alpha} g^q_{\beta}}{Q^2 + M^2_Z} + \eta^e_{\alpha\beta}
\]

CI modify the tree level $eq\rightarrow eq$ scattering amplitudes.

At LEP and Tevatron:

\[
L_{CI} = \sum_{\alpha, \beta} \eta^e_{\alpha\beta}(\bar{e}_\alpha \gamma^\mu e_\alpha)(\bar{q}_\beta \gamma^\mu q_\beta)
\]

where $\alpha$ and $\beta$ are electron and quark helicities (L,R).

e+p sensitive to $\eta^e_{LL}$ and $\eta^e_{RR}$
e+p sensitive to $\eta^e_{LR}$ and $\eta^e_{RL}$
CI, General Models

Also referred to as Compositeness Models.

Couplings \( \eta_{eq}^{\alpha\beta} \) are related to the mass scale \( \Lambda \) at which new interactions accour:

\[
\eta_{eq}^{\alpha\beta} = \frac{\varepsilon g_{CI}^2}{\Lambda^2}
\]

\( g_{CI} \) is a coupling strength of new interactions and \( \varepsilon = \pm 1 \).

By convention \( g_{CI}^2 = 4\pi \).

Different models assume different helicity structure of new interactions, given by set of couplings \( \eta_{eq}^{\alpha\beta} \) (4 for every q flavour).

Parity conserving models fulfill the relation:

\[
\eta_{eq}^{LL} + \eta_{eq}^{LR} - \eta_{eq}^{RL} - \eta_{eq}^{RR} = 0
\]

Family universality assumed.
CI, General Models

ZEUS CI analysis based on full NC sample of $L=0.44$ fb$^{-1}$ (with recently included NC $e^+p$ data).

ZEUS (94-06 data):

- $\Lambda^- > 3.8$ - 8.9 TeV (95% C.L.)

ZEUS (94-07 data): $\Lambda^- > 3.8$ - 8.9 TeV (95% C.L.)

ZEUS

- $N/N_{exp}$ vs $Q^2 (GeV^2)$ for Contact Interactions Limits (prel.)

- $E_\perp$ and $E_{miss}$ vs $Q^2 (GeV^2)$

ZEUS (prel.) $e^+p$ vs $Q^2 (GeV^2)$

- VV $\Lambda^- = 8.0$ TeV
- VV $\Lambda^+ = 8.9$ TeV

- AA $\Lambda^- = 7.0$ TeV
- AA $\Lambda^+ = 6.7$ TeV

ZEUS (prel.) $e^+p$ vs $Q^2 (GeV^2)$

- VV $\Lambda^- = 8.0$ TeV
- VV $\Lambda^+ = 8.9$ TeV

ZEUS 94-06 (prel.) $e^+p$ vs $Q^2 (GeV^2)$

- VA $\Lambda^- = 3.8$ TeV
- X1 $\Lambda^- = 5.1$ TeV
- X2 $\Lambda^- = 5.4$ TeV
- X3 $\Lambda^- = 5.6$ TeV
- X4 $\Lambda^- = 6.0$ TeV
- X5 $\Lambda^- = 6.2$ TeV
- X6 $\Lambda^- = 6.4$ TeV
- U1 $\Lambda^- = 6.6$ TeV
- U2 $\Lambda^- = 6.8$ TeV
- U3 $\Lambda^- = 6.8$ TeV
- U4 $\Lambda^- = 7.0$ TeV
- U5 $\Lambda^- = 7.2$ TeV
- U6 $\Lambda^- = 7.4$ TeV
- LL $\Lambda^- = 7.5$ TeV
- LR $\Lambda^- = 7.5$ TeV
- RL $\Lambda^- = 7.5$ TeV
- RR $\Lambda^- = 7.5$ TeV

ZEUS 94-07 (prel.) $e^+p$ vs $Q^2 (GeV^2)$

- $-1/\Lambda^2$ best fit value
- $+1/\Lambda^2$ best fit value

ZEUS (94-07 data): $\Lambda^- > 3.8$ - 8.9 TeV (95% C.L.)
Leptoquarks Production

The Buchmueller-Rueckl-Wyler Model

Leptoquarks (LQ) - hypothetical boson connecting lepton and quark sectors. Carry SU(3) colour, fractional electric charge, lepton (L), barion (B) and fermion number $F=3B+L=0,2$. Conserve SM symmetries. Chiral objects i.e. either left- or right-handed coupling to lepton, but not both.

7 scalar and 7 vector LQs coupling to eq. 4 LQs couple also to $\nu q$.

At HERA LQs can be resonantly produced in s-channel ($M_{LQ} < \sqrt{s}$, with $\Gamma=\lambda^2 M_{LQ}$) or exchanged in u-channel.

$\lambda$ is the Yukawa LQ-$e$-$q$ coupling.

Limit setting on $M_{LQ}/\lambda$.

<table>
<thead>
<tr>
<th>$F=2$</th>
<th>Prod./Decay</th>
<th>$\beta_\epsilon$</th>
<th>$F=0$</th>
<th>Prod./Decay</th>
<th>$\beta_\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+ p$</td>
<td>Scalar Leptoquarks $e^+ p$</td>
<td></td>
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</tr>
<tr>
<td>$S_{0.L}$</td>
<td>$e^- u_L \rightarrow e^- u$</td>
<td>$1/2$</td>
<td>$S_{1/2,L}$</td>
<td>$e^+ u_R \rightarrow e^+ u$</td>
<td>$1$</td>
</tr>
<tr>
<td>$S_{0.R}$</td>
<td>$e^- u_R \rightarrow e^- u$</td>
<td>$1$</td>
<td>$S_{1/2,R}$</td>
<td>$e^+ u_L \rightarrow e^+ u$</td>
<td>$1$</td>
</tr>
<tr>
<td>$S_{0.L}$</td>
<td>$e^- d_R \rightarrow e^- d$</td>
<td>$1$</td>
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<td>$S_{0.R}$</td>
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</tbody>
</table>

| | | |

| $V_{1/2,R}$ | $e^- d_R \rightarrow e^- d$ | $1$ | $V_{0,R}$ | $e^- d_L \rightarrow e^- d$ | $1$ |
| $V_{1/2,L}$ | $e^- u_R \rightarrow e^- u$ | $1$ | $V_{0,L}$ | $e^- d_L \rightarrow e^- d$ | $1/2$ |
| | | | | | |
| $V_{1/2,R}$ | $e^- d_R \rightarrow e^- d$ | $1$ | $\tilde{V}_{0,R}$ | $e^- u_R \rightarrow e^- u$ | $1$ |
| $V_{1/2,L}$ | $e^- u_R \rightarrow e^- u$ | $1$ | $V_{1,L}$ | $e^- d_L \rightarrow e^- d$ | $1/2$ |

18/07/2009  Search for LQ and CI R. Ciesielski
1st Generation Leptoquarks

H1 analysis based on full NC and CC samples of \( L = 0.45 \) fb\(^{-1}\)

\[ \text{LQ} \rightarrow \text{eq} \]

Large SM background from NC and CC processes.

Good description of data by SM prediction (also for CC, for \( e^+p \) and \( e^-p \) separately and for polarized samples). No LQ signal observed.

**Limits set for all 14 LQs.**

**H1 (94-07 data):** For \( \lambda = \sqrt{4\pi\alpha} = 0.3 \)

\[ M_{\text{LQ}} < 291-330 \text{ GeV} \] are excluded at 95\% C.L.

**ZEUS CI (94-07 data):**

\[ n_{eq}^\alpha \propto \left( \frac{\lambda}{M_{\text{LQ}}} \right)^2 \]

\[ M_{\text{LQ}}/\lambda > 0.41-1.88 \text{ TeV} @95\% \text{ C.L.} \]

**LEP (OPAL, L3):** indirect constraints from \( ee \rightarrow qq \).

**Tevatron (D0):** LQ+LQ pair production from qq annihilation or gg fusion (\( \lambda \) independent).
2\textsuperscript{nd} Generation Leptoquarks

Search for Lepton Flavour Violation

$e^+p\rightarrow LQ\rightarrow \mu X$ with $e^+p$ data.

Search for Lepton Flavour Violation mediated by LQ. Experimentaly clear process. Background dominated by lepton pair production. No evidence for signal.

Limits set for 7 LQs ($F=2$), under assumption: $\lambda_{\mu q} = \lambda_{eq}$, $\lambda_{\tau q} = 0$.

For $\lambda = \sqrt{4\pi\alpha} = 0.3$
$M_{LQ} < 291\text{–}433$ GeV are excluded at 95\%C.L.
Summary

- Search for deviations from SM in High-$Q^2$ $e^+p$ and $e^-p$ DIS data has been performed by ZEUS and H1 based on full datasets of $\sim 0.45 \text{ fb}^{-1}$ (per experiment).

- No deviations have been found.

- ZEUS (NC DIS): 95% C.L. limits have been set for different CI models.

- H1 (NC, CC DIS): 95% C.L. limits have been set for resonant and non-resonant LQ production.

- HERA limits complementary to Tevatron and LEP limits.
4-fermion CI at HERA:

\[
M_{\alpha\beta}^{\text{eq}}(Q^2) = \frac{e^2 e_q}{Q^2} - \frac{e^2}{\sin^2 \theta_W \cos^2 \theta_W} \frac{g_{\alpha}^e g_{\beta}^q}{Q^2 + M_Z^2} + \eta_{\alpha\beta}^{\text{eq}}
\]

\(\alpha, \beta\) - electron and quark helicities (L,R).

NC e⁻p scattering:

\[
\frac{d^2 \sigma(e^- p)}{dx dy} = \frac{sx}{16 \pi} \sum q(x) \left[ P_- M_{LL}^2 + P_+ M_{RR}^2 + (1-y)^2 \left( P_- M_{LR}^2 + P_+ M_{RL}^2 \right) \right]
\]

NC e⁺p scattering:

\[
\frac{d^2 \sigma(e^+ p)}{dx dy} = \frac{sx}{16 \pi} \sum q(x) \left[ P_+ M_{LL}^2 + P_- M_{RR}^2 + (1-y)^2 \left( P_+ M_{LR}^2 + P_- M_{RL}^2 \right) \right]
\]

At high \(Q^2\) and high \(x\) quark distribution dominate (valence quarks).
Some contributions are suppressed by helicity factor \((1-y)^2\).
NC e⁻p sensitive to LL and RR, NC e⁺p sensitive to LR and RL configurations.

**SM MEs modified by quark form-factor:**

\[
M_{\alpha\beta}^{\text{eq}}(Q^2) = M_{\alpha\beta}^{\text{eq}}(Q^2)_{\text{SM}} (1 - R_q^2 Q^2 / 6)
\]

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**CI, Heavy Leptoquarks**

The Buchmueller-Rueckl-Wyler Model

At HERA can be resonantly produced in s-channel ($M_{LQ} < \sqrt{s}$) or exchanged in u-channel.

For high mass LQs ($M_{LQ} \gg \sqrt{s}$) virtual production/exchange results in the effective CI coupling:

$$\eta_{eq} = a_{eq} \left( \frac{\lambda}{M_{LQ}} \right)^2$$

where $a_{eq}^{\alpha \beta}$ is a coefficient and $\lambda$ is the Yukawa LQ-e-q coupling.

Limit setting on $M_{LQ}/\lambda$. 

<table>
<thead>
<tr>
<th>Model</th>
<th>$a_{LL}^{ed}$</th>
<th>$a_{LR}^{ed}$</th>
<th>$a_{RL}^{ed}$</th>
<th>$a_{RR}^{ed}$</th>
<th>$a_{LL}^{eu}$</th>
<th>$a_{LR}^{eu}$</th>
<th>$a_{RL}^{eu}$</th>
<th>$a_{RR}^{eu}$</th>
</tr>
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<tbody>
<tr>
<td>$S_L^L$</td>
<td>$+\frac{1}{2}$</td>
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<td>$S_R^L$</td>
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<td>$+\frac{1}{2}$</td>
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<tr>
<td>$S_0^L$</td>
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<td>$-\frac{1}{2}$</td>
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<tr>
<td>$S_0^R$</td>
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<td>$-\frac{1}{2}$</td>
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<tr>
<td>$S_{1/2}^L$</td>
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<td>$+\frac{1}{2}$</td>
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<tr>
<td>$S_{1/2}^R$</td>
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<td>$+\frac{1}{2}$</td>
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<tr>
<td>$V_L^L$</td>
<td>$-1$</td>
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<td>$V_R^L$</td>
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<td>$V_0^L$</td>
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<td>$-1$</td>
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<tr>
<td>$V_L^{1/2}$</td>
<td>$+1$</td>
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<tr>
<td>$V_R^{1/2}$</td>
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<td>$+1$</td>
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<tr>
<td>$V_0^{1/2}$</td>
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<td>$+1$</td>
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<td>$V_1$</td>
<td>$-1$</td>
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<td>$-2$</td>
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</tbody>
</table>
CI, Heavy Leptoquarks

ZEUS Preliminary 1994-2007 $e^\pm p$

<table>
<thead>
<tr>
<th>Model Coupling Structure</th>
<th>$M_{LQ}/\lambda_{LQ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S^L_o$</td>
<td>$a_{eL}^{eL} = +\frac{1}{2}$</td>
</tr>
<tr>
<td>$S^R_o$</td>
<td>$a_{eR}^{eR} = +\frac{1}{2}$</td>
</tr>
<tr>
<td>$S^R_o$</td>
<td>$a_{ed}^{ed} = +\frac{1}{2}$</td>
</tr>
<tr>
<td>$S^{1/2}_L$</td>
<td>$a_{eL}^{eL} = -\frac{1}{2}$</td>
</tr>
<tr>
<td>$S^{1/2}_R$</td>
<td>$a_{eL}^{eL} = -\frac{1}{2}$</td>
</tr>
<tr>
<td>$S^+_L$</td>
<td>$a_{eL}^{eL} = +1$, $a_{eL}^{eL} = +\frac{1}{2}$</td>
</tr>
<tr>
<td>$V^+_L$</td>
<td>$a_{eL}^{eL} = -1$</td>
</tr>
<tr>
<td>$V^+_R$</td>
<td>$a_{eL}^{eL} = -1$</td>
</tr>
<tr>
<td>$V^{+_R}$</td>
<td>$a_{eL}^{eL} = -1$</td>
</tr>
<tr>
<td>$V^{-_L}$</td>
<td>$a_{eL}^{eL} = +1$</td>
</tr>
<tr>
<td>$V^{+_L}$</td>
<td>$a_{eL}^{eL} = +1$</td>
</tr>
<tr>
<td>$V^{-_L}$</td>
<td>$a_{eL}^{eL} = -1$</td>
</tr>
<tr>
<td>$V^+_L$</td>
<td>$a_{eL}^{eL} = +1$</td>
</tr>
</tbody>
</table>

Only sensitive to $M_{LQ}/\lambda$.

ZEUS (94-07 data): $M_{LQ}/\lambda > 0.41 - 1.88$ TeV (95% C.L.)

18/07/2009
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1\textsuperscript{st} Generation Leptoquarks

**NC:**

Leptoquark Search, HERA II

- LH $e^p$
  - $e^p$ (104 pb$^{-1}$)
  - $P = -26\%$

- RH $e^p$
  - $e^p$ (99 pb$^{-1}$)
  - $P = +31\%$

**CC:**

Leptoquark Search, HERA II

- H1
  - $e^p$ (104 pb$^{-1}$)
  - $P = -26\%$

- H1
  - $e^p$ (99 pb$^{-1}$)
  - $P = +31\%$
1st Generation Leptoquarks

Limits for all 14 LQs.

\[ M_{\text{LQ}} < \sqrt{s} = 300 \text{ GeV} \]
resonant production
stronger limits.

\[ M_{\text{LQ}} > \sqrt{s}, \text{ only } u\text{-channel} \]
exchange, CI region.

For \( \lambda = \sqrt{4\pi \alpha} = 0.3 \)
\[ M_{\text{LQ}} < 291-330 \text{ GeV} \] are excluded at 95\% C.L.
2\textsuperscript{nd} Generation Leptoquarks

$e^+p \rightarrow LQ \rightarrow \mu X$ with $e^+p$ data.

Search for Lepton Flavour Violation mediated by LQ.

Limits set for 7 LQs (F=2), under assumption $\lambda_{\mu q} = \lambda_{eq}$, $\lambda_{\tau q} = 0$.

For $\lambda = \sqrt{4\pi\alpha} = 0.3$

$M_{LQ} < 291$-433 GeV are excluded at 95\% C.L.
H1 analysis based on HERA-I data. (DESY 07-009)

Limits set for 14 LQs, under assumption $\lambda_{\tau q} = \lambda_{eq}$