Search for First Generation Leptoquarks at HERA.

David South (DESY) on behalf of the H1 Collaboration

The H1 experiment at HERA

- H1 detector operated 1992-2007, asymmetric design
- HERA II phase with longitudinally polarised $e^\pm$ beam
- Luminosity of full H1 high energy data $\sim 0.5$ fb$^{-1}$
- Initial $e^\pm p$ state: Ideal machine to find Leptoquarks

Centre of mass $\sqrt{s} = 319$ GeV
Leptoquark basics

> Leptoquarks are hypothetical colour triplet bosons, with fractional charge, with both lepton and baryon number \( \neq 0 \)

> Couple to both quarks and leptons (as well as gluons)

> Parameterised in terms of mass \( M_{LQ} \), coupling \( \lambda \) and quantum numbers

> The most general model with respect to the SM symmetry groups \( SU(3)_c \times SU(2)_L \times U(1)_Y \) results in the 14 different LQ types*

> Classified by weak isospin, charge, spin and chirality, where the fermion number \( F = | L + 3B | = 0, 2 \)

> LQ decays to \( \mu q \) or \( \tau q \) imply lepton flavour violation (LFV)

Leptoquarks at HERA: Production

s-channel: resonant production
For $M_{LQ} \leq (sx)^{1/2}$
Cross section $\sigma \sim \lambda^2$

u-channel: LQ exchange
For $M_{LQ} > s^{1/2}$
Cross section $\sigma \sim \lambda^4$

- For LQ masses up to the centre of mass at HERA, resonant production in the s-channel dominates
  - Electron-proton collisions, mainly $F = |L + 3B| = 2$ LQs produced
  - Positron-proton collisions, mainly $F = |L + 3B| = 0$ LQs produced
- For LQ masses well above $319$ GeV, the u-channel also contributes: $e^-p$ and $e^+p$ similar sensitivity to $F = 0$, $2$ LQs
- LQ are chiral particles, gain in sensitivity at HERA II due to polarised lepton beam

1st gen: $eq \rightarrow LQ \rightarrow e(\nu)q$
2nd gen: $eq \rightarrow LQ \rightarrow \mu(\nu)q$
3rd gen: $eq \rightarrow LQ \rightarrow \tau(\nu)q$  \{ LFV \}

Polarisation dependence

For $M_{LQ} (GeV)$

- $P_e = +0.6$
- $P_e = -0.6$

For $M_{LQ} (GeV)$

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Leptoquarks at HERA: Decay

First generation search: \( LQ \to e(\nu)q \)
- Some LQs decay to neutrino-quark as well as electron-quark: search in NC/CC DIS
- Gauge invariance leads to a branching fraction
  \[ \beta_\ell = \frac{\Gamma_{\ell q}}{\Gamma_{\ell q} + \Gamma_{\nu q}} = 0.5 \]
- Interference with SM NC/CC (identical final state) included in the model

Second and third generation searches: \( LQ \to \mu q, \tau q \)
- No CC contributions considered in the analysis, neutrino flavours indistinguishable
- Branching ratio
  \[ \beta = \beta_\ell \times \beta_{LFV} \quad \text{with} \quad \beta_{LFV} = \frac{\Gamma_{\mu(\tau)q}}{\Gamma_{\mu(\tau)q} + \Gamma_{eq}} \]  
  \[ \Gamma_{\ell q} = m_{LQ} \lambda_{eq}^2 \times \left\{ \begin{array}{ll} \frac{1}{16\pi} & \text{scalar} \\ \frac{1}{24\pi} & \text{vector} \end{array} \right. \]
- Assuming lepton universality, and that only one LFV transition is possible, \( \beta_{LFV} = 0.5 \)
- No LFV transition: first generation only

\( \Rightarrow \text{LFV} \)
### 14 LQ types in the BRW model

<table>
<thead>
<tr>
<th>Type</th>
<th>$J$</th>
<th>$F$</th>
<th>$Q$</th>
<th>$e p$ dominant process</th>
<th>Coupling</th>
<th>Branching ratio $\beta_\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S^L_0$</td>
<td>0</td>
<td>2</td>
<td>$-1/3$</td>
<td>$e^-_L u_L \rightarrow \ell^- u$</td>
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<td>2</td>
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<td>$e^-_L d_L \rightarrow \ell^- d$</td>
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<td>1</td>
</tr>
<tr>
<td>$S^L_1$</td>
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<td>2</td>
<td>$-1/3$</td>
<td>$e^-_L u_L \rightarrow \ell^- u$</td>
<td>$-\lambda_L$</td>
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</tr>
<tr>
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<td>0</td>
<td>2</td>
<td>$-4/3$</td>
<td>$e^-_L d_L \rightarrow \ell^- d$</td>
<td>$-\sqrt{2}\lambda_L$</td>
<td>1</td>
</tr>
<tr>
<td>$V^L_{1/2}$</td>
<td>1</td>
<td>2</td>
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<td>$e^+_R d_L \rightarrow \ell^+ u$</td>
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For ease of comparison to hadron collider limits:

$$\beta_\ell = 1.0 \text{ LQ}_S : S^R_0 \ S^R_0 \ V^L_{1/2} \ V^R_{1/2} \ V^L_{1/2} \ V^R_{1/2} \ \bar{V}^R_0 \ \bar{V}^R_0 \ S^L_{1/2} \ S^R_{1/2} \ \bar{S}^L_{1/2}$$

$$\beta_\ell = 0.5 \text{ LQ}_S : S^L_0 \ V^L_0$$
High $Q^2$ measurements from H1

> H1 recently completed the high $Q^2$ programme of measurements
> Much information contained in the complete NC and CC analysis

- See ICHEP talk by Z. Zhang, as well as the publication: arXiv:1206.7007
First Generation Search Background: High $Q^2$ NC and CC

- Final state indistinguishable from SM NC/CC DIS: jet + electron/neutrino
  - Selection based on the inclusive DIS analyses
  - Look for enhancements in mass spectra

Main NC Selection Criteria
- Isolated electron
- $E_e > 11$ GeV
- $Q_e^2 > 500$ GeV$^2$
- $0.1 < y_e < 0.9$

Main CC Selection Criteria
- $P_T^{\text{miss}} > 12$ GeV
- $Q_h^2 > 1000$ GeV$^2$
- $0.1 < y_h < 0.9$
First Generation Leptoquark Search

Good description of the full HERA I+II H1 data set by the MC prediction, with no significant deviation from SM

David South | Search for First Generation Leptoquarks at HERA | ICHEP 2012, 4-11 July 2012 | Page 9
First Generation Leptoquark Search: Polarisation Periods

- Analysis of different polarisation periods in HERA II data
- Good description of the H1 data by the SM prediction
- No evidence for LQ signal: interpret in terms of exclusion limits
First Generation Leptoquark Limits for all 14 LQ types

For $\lambda=0.3$ LQ masses up to 800 GeV are ruled out @ 95% CL
First Generation Leptoquark Search: Example Limits

- H1 limits in the resonant LQ production region now superseded by those from the Tevatron and LHC (pair production, independent of $\lambda$)

- Still some H1 sensitivity in the CI region, for large values of $\lambda$
Summary and conclusions

> The ep collisions at the HERA collider are the ideal environment to search for leptoquarks

  - Searches for LQs of all generations have been performed by the H1 experiment using the complete high energy data taken at $\sqrt{s} = 319$ GeV

> No significant deviation from the SM observed and limits are set on the production of such particles

  - For large values of the coupling $\lambda$, HERA limits in CI region are still beyond current limits from hadron colliders
  - LQ masses up to 800 GeV are ruled out @ 95% CL for $\lambda = 0.3$

**Final H1 search papers:**

## Table of Scalar LQ mass limits from hadron colliders

<table>
<thead>
<tr>
<th>Scalar LQs</th>
<th>1st Gen</th>
<th>2nd Gen</th>
<th>3rd Gen</th>
</tr>
</thead>
<tbody>
<tr>
<td>β</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>ATLAS</td>
<td>660(^1)</td>
<td>607(^1)</td>
<td>685(^2)</td>
</tr>
<tr>
<td>CMS</td>
<td>384(^3)</td>
<td>340(^4)</td>
<td>632(^5)</td>
</tr>
<tr>
<td>DØ</td>
<td>299(^7)</td>
<td>326(^8)</td>
<td>316(^9)</td>
</tr>
<tr>
<td>CDF</td>
<td>236(^{11})</td>
<td>205(^{11})</td>
<td>226(^{12})</td>
</tr>
</tbody>
</table>

6. “Search for pair production of third-generation scalar leptoquarks using events produced in pp collisions at sqrt(s)=7 TeV containing b-jets and missing transverse energy”, CMS PAS EXO-11-030.