Search for Excited Leptons and Quarks at HERA

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For H1 Collaboration
H1 and HERA 1994-2007

- H1 detector at HERA, asymmetric design
- Large increase in data from HERA II and polarised e±p data
- Final H1 dataset: e±p: 184 pb⁻¹; e±p: 475 pb⁻¹
- Presented here: Excited Leptons and Quarks

HERA I: 120 pb⁻¹ /exp
HERA II:
- Lumi upgrade
- Polarised leptons beam

Status: 1-July-2007

HERA-1
1994-2000

HERA-2
2003-2007

√s = 301/319 GeV

p (820/920 GeV)
e⁺p

e⁻p

820 GeV
920 GeV

Days of running

H1 Integrated Luminosity / pb⁻¹

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Excited fermion states generalities
Basic elements of the gauge mediated theory

- Excited fermion states should be a signal for substructure at a characteristic scale \( O(\Lambda) \) (Actual experimental constraints lead to a scale \( \Lambda > \sim 1 \text{ TeV} \))
- If known quarks and leptons are composite they should be considered, as the ground state to a rich spectrum of excited states
- Composite models of fermions:
  - should explain the threefold “replica” of fermion generation
  - should be possible alternatives to the conventional SM description of EW symmetry breaking.

- The ways to couple fermions and excited fermions:

  **Gauge mediated interactions (GM):**
  - \( f^* \) can carry different spin/isospin values
    Assume that \( f^* \) have spin 1/2 - isospin 1/2 and are organised in left/right weak doublet
  - Lagrangian should respect a chiral symmetry
    \( \rightarrow \) Only right-handed part of \( F^* \) involved in \( fF^*V \) couplings
  - Interactions described in a SU(2)XU(1) invariant form

\[
\mathcal{L}_{GM} = \frac{1}{2\Lambda} F_{R}^{-a} \bar{u}_{L}^{a} \left[ g f \frac{T_{a}}{2} W_{\mu \nu}^{a} + g' f' \frac{\not{Y}}{2} B_{\mu \nu} + g_{S} f_{S} \frac{\not{\Lambda}}{2} G_{\mu \nu}^{a} \right] \bar{L}_{R} + \text{h.c.}
\]

- or **Contact** interactions – considered for \( e^* \): see later (U.Baur et al, Phys. Rev 42, 815, 1990)
Excited fermions: production and decay at ep colliders

ν*: produced via t-channel W boson exchange
\[ \sigma(e^-p)/\sigma(e^+p) \sim 100, \; M_{\nu^*}=200 \text{ GeV} \]
(“charged current” like production)

H1 analysis: use all e^-p data (184 pb^-1)

q*: Under the assumption:
- \( f_s = 0 \)
- \( f = f' \)
- (q* prod. via qg = 0)
- (q* decay into qg = 0)

Similar signatures for e* and ν*

f* de-excitation by emission of γ, Z, W

e*: produced via t-channel γ/Z bosons exchange
- contact interactions

H1 analysis: use all e^±p data (475 pb^-1)

Results complementary to the q* searches performed at the Tevatron (f_s ≠ 0).
The effect of non-zero values of f_s is also studied.

f* de-excitation by emission of γ, Z, W

H1 analysis: use all e^±p data (475 pb^-1)
Searches for $q^*$ with H1 ($e^\pm p$, 475 pb$^{-1}$)

**channel**

$q^* \rightarrow q\gamma$
- 1 isolated electromagnetic cluster with $P_T^{\gamma} > 35$ GeV
- at least 1 jet with $P_T^{\text{jet}} > 20$ GeV
- Reduced NC-DIS: no other isolated electron with $E_e > 10$ GeV in LAr

$q^* \rightarrow qW/Z \rightarrow qqq$
- at least 3 jets with $P_T^{\text{jets}} > 50, 30, 15$ GeV
- Reduced multi-jet photoproduction: highest $P_T$ jet is not associated to the $W$ or $Z$ candidate

$q^* \rightarrow qW \rightarrow q\ell v$
- $P_T^{\text{miss}} + e + \text{jet}$ bkg: NC-DIS and photoproduction

$q^* \rightarrow qW \rightarrow q\mu\nu$
- $P_T^{\text{miss}} + \mu + \text{jet}$ bkg: SM $W$ production

$q^* \rightarrow qZ \rightarrow qee$
- jet + 2$e$ bkg: $e^-$ pairs

$q^* \rightarrow qZ \rightarrow q\mu\mu$
- jet + 2$\mu$ bkg: $\mu^-$ pairs

- $u$-channel included for the exchange of excited quarks
- Non-negligible cross section for the high $q^*$ masses and low values of $\Lambda$. 
Searches for $q^*$ with H1 ($e^\pm p$, 475 pb$^{-1}$)

- Good agreement with the SM and no resonance observed in mass spectra
- Derive limits @ 95% C.L. on $f/\Lambda$ as a function of $M_{q^*}$ for all channels combined
- Conventional assumptions:
  - $f_s = 0$ (no s interactions)
  - $f, f'$ comparable; only examine $f = +f'$

<table>
<thead>
<tr>
<th>Channel</th>
<th>Data</th>
<th>SM</th>
<th>Signal Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q^* \rightarrow q\gamma$</td>
<td>44</td>
<td>46 ± 8</td>
<td>35 – 45</td>
</tr>
<tr>
<td>$q^* \rightarrow qW/Z \rightarrow qq\bar{q}$</td>
<td>341</td>
<td>326 ± 78</td>
<td>5 – 55</td>
</tr>
<tr>
<td>$q^* \rightarrow qW \rightarrow q\gamma$</td>
<td>6</td>
<td>6.0 ± 0.8</td>
<td>20 – 30</td>
</tr>
<tr>
<td>$q^* \rightarrow qW \rightarrow q\mu\nu$</td>
<td>5</td>
<td>4.4 ± 0.7</td>
<td>20 – 40</td>
</tr>
<tr>
<td>$q^* \rightarrow qZ \rightarrow qee$</td>
<td>0</td>
<td>0.44 ± 0.08</td>
<td>15 – 30</td>
</tr>
<tr>
<td>$q^* \rightarrow qZ \rightarrow q\mu\mu$</td>
<td>0</td>
<td>0.87 ± 0.11</td>
<td>15 – 30</td>
</tr>
</tbody>
</table>
Limits on $f/\Lambda$ from q* production

Limits at 95% C.L. on $f/\Lambda$ from all channels combined

- Limit driven by $q^* \to q\gamma$ at low mass, W/Z decays contribute at higher masses
- Limits greatly improved with respect to HERA I limit

HERA: Best sensitivity for masses beyond the LEP reach
**Searches for $\nu^*$ with H1 ($e^-p$, 184 pb$^{-1}$)**

### Search for $\nu^*$ at HERA ($e^-p$, 184 pb$^{-1}$)

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>$\nu^*\rightarrow\nu\gamma$</td>
<td>7</td>
<td>12.3 ± 3.0</td>
<td>50–55</td>
</tr>
<tr>
<td>$\nu^*\rightarrow eW\rightarrow eq\bar{q}$</td>
<td>220</td>
<td>223 ± 47</td>
<td>40–65</td>
</tr>
<tr>
<td>$\nu^*\rightarrow eW\rightarrow e\nu\mu$</td>
<td>0</td>
<td>0.40 ± 0.05</td>
<td>35</td>
</tr>
<tr>
<td>$\nu^*\rightarrow eW\rightarrow eve$</td>
<td>0</td>
<td>0.7 ± 0.1</td>
<td>45</td>
</tr>
<tr>
<td>$\nu^*\rightarrow \nu Z\rightarrow \nu q\bar{q}$</td>
<td>89</td>
<td>95 ± 21</td>
<td>25–55</td>
</tr>
<tr>
<td>$\nu^*\rightarrow \nu Z\rightarrow vee$</td>
<td>0</td>
<td>0.19 ± 0.05</td>
<td>45</td>
</tr>
</tbody>
</table>

- Good agreement with the SM and no resonance observed in mass spectra
- Derive limits @ 95% C.L. on $f/\Lambda$ as a function of $M_{\nu^*}$ for channels combined
- Conventional assumptions:
  - $\nu^*$ is insensitive to $f_s (=0)$
  - $f, f'$ comparable; examine $f = -f'$ or $f = +f'$

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Limits at 95% C.L. on $f/\Lambda$ from all channels combined

Limit driven by $\nu^* \rightarrow \nu\gamma$ at low mass, $\nu^* \rightarrow eW$ contributes for $M > 200$ GeV

HERA: Best sensitivity for masses beyond the LEP reach
Searches for e* with H1 (e±p, 475 pb⁻¹)

**Search for e* at HERA (475 pb⁻¹)**

<table>
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<tr>
<th>Channel</th>
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<th>SM</th>
<th>Signal Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>e*→eγ (ela.)</td>
<td>42</td>
<td>48 ± 4</td>
<td>60–70</td>
</tr>
<tr>
<td>e*→eγ (inel.)</td>
<td>65</td>
<td>65 ± 8</td>
<td>60–70</td>
</tr>
<tr>
<td>e*→νW→νq̅q̅</td>
<td>129</td>
<td>133 ± 32</td>
<td>20–55</td>
</tr>
<tr>
<td>e*→νW→νeν</td>
<td>4</td>
<td>4.5 ± 0.7</td>
<td>35</td>
</tr>
<tr>
<td>e*→eZ→eνν</td>
<td>286</td>
<td>277 ± 62</td>
<td>20–55</td>
</tr>
<tr>
<td>e*→eZ→eq̅q̅</td>
<td>0</td>
<td>0.72 ± 0.06</td>
<td>60</td>
</tr>
<tr>
<td>e*→eZ→ee</td>
<td>0</td>
<td>0.52 ± 0.05</td>
<td>40–15</td>
</tr>
</tbody>
</table>

• **Good agreement** with the SM and **no resonance** observed in mass spectra
• Derive limits @ 95% C.L. on f/Λ as a function of M_e* for channels combined
• Conventional assumptions:
  - e* is insensitive to fs (s=0)
  - f = ±f' only (e*→eγ, high BR, forbidden for f = -f')
Limits on $f/\Lambda$ from $e^*$ production

Limits at 95% C.L. on $f/\Lambda$ from all channels combined

**HERA: Best sensitivity in the intermediate $e^*$ mass range**

$M_{e^*} < 272$ GeV excluded for $f/\Lambda = 1/M_{e^*}$

- Limit driven by $e^* \rightarrow e\gamma$ at low mass, $e^* \rightarrow \nu W$ contributes at higher masses
- Results from LEP (OPAL, DELPHI) and from CDF ($e^*$ within GM model) also shown

Relation:

\[ \frac{1}{\Lambda} = \frac{1}{M_{e^*}} \]

**For a given mass, CI contribution decreases for increasing $\Lambda$**

- For $e^*$ masses below 250 GeV, the additional contribution of CI to $e^*$ production changes the limit by a factor 1.15  $\rightarrow$ 1.2

- In addition to the GM interactions, a CI model can be used to describe the $f \leftrightarrow f^*$ transitions, described by:

\[ \mathcal{L}_{CI} = \frac{4\pi}{2\Lambda^2} \, j^2, \]

with left-handed fermion currents.

- Total $e^*$ production cross section is the sum of the cross sections $\sigma_{GM,CI}$

For simplicity, set $f = +f^* = 1$, fixing the relative strength of the GM and CI components and use only GM $e^*$ decays (> 95% of total here)
Summary— for 200 GeV < \( M_{f^*} < 300 \) GeV, HERA has the best sensitivity.

**Search for \( \nu^* \) at HERA (e\(^\pm\)p, 184 pb\(^{-1}\))**

All the H1 data at \( E_{cm} = 301, 319 \) GeV have been used:

- \( e^p : 184 \) pb\(^{-1}\) excited neutrino (published)
- \( e^p : 475 \) pb\(^{-1}\) excited electrons (published) and excited quarks (to be published)

No signal found and improved upper limits have been derived:

- For \( \nu^* : M_{\nu^*} < 213 \) GeV excluded
- For \( e^* : M_{e^*} < 272 \) GeV excluded
- For \( q^* : M_{q^*} < 252 \) GeV excluded

**Search for \( e^* \) at HERA (475 pb\(^{-1}\))**

**Search for \( q^* \) at HERA (475 pb\(^{-1}\))**
Back-up slides
Expression of the $V_{f\bar{f}^*}$ couplings ($V = \gamma, Z, W$)

- $f^*\gamma$ vertex
  
  $$C_{\gamma f^*} = \frac{1}{2} (f I_3 + f' \frac{\gamma}{2})$$

- $f^*Z$ vertex
  
  $$C_{Z f^*} = \frac{1}{2} (f I_3 \cot \theta_W - f' \frac{\gamma}{2} \tan \theta_W)$$

- $f^*W$ vertex
  
  $$C_{W f^*} = \frac{f}{2\sqrt{2} \sin \theta_W}$$

\[\begin{align*}
C_{\gamma \nu \nu^*} &= \frac{1}{4} (f - f') = 0 |f = f' \rangle \\
C_{\gamma e e^*} &= -\frac{1}{4} (f + f') = 0 |f = -f' \rangle
\end{align*}\]

$I_3$: third isospin component

$\gamma$: hypercharge ($\pm 1$ for $\ell^*$)

$\theta_W$: Weinberg angle

### $e^*$ Limits including the CI Production Model

- In addition to the GM interactions, a CI model can be used to describe the $f \leftrightarrow f^*$ transitions, described by:

$$\mathcal{L}_{CI} = \frac{4 \pi}{2 \Lambda^2} j^\mu j_\mu \quad \text{with} \quad j_\mu = \eta_L \bar{F}_L^* \gamma_\mu F_L + \eta'_L \bar{F}_L^* \gamma_\mu F_L + \eta''_L \bar{F}_L^* \gamma_\mu F_L^* + \text{h.c.} + (L \rightarrow R)$$

  with left-handed fermion currents.

- Total $e^*$ production cross section is the sum of the cross sections $\sigma_{GM+CI}$

- For simplicity, set $f = +f' = 1$, fixing the relative strength of the GM and CI components and use only GM $e^*$ decays (> 95% of total here)
Limits on $f/\Lambda$ from $q^*$ production

Limits at 95% C.L. on $f/\Lambda$ from all channels combined

- $f = f', \Lambda = M_{q^*}$
- this limit is derived using $\gamma/Z/W$ decay channels of $q^*$

For $f_s < 0.1$ and for $M_{q^*} < 190$ GeV, the present analysis probes a domain not excluded by Tevatron experiments