Searches for Isolated Leptons, Multileptons and Leptoquarks at HERA

Judith Katzy (DESY)
Total luminosity collected:

**H1:** 478 pb$^{-1}$
- 294 pb$^{-1}$ $e^+$
- 184 pb$^{-1}$ $e^-$

**Zeus:** 492 pb$^{-1}$
- 286 pb$^{-1}$ $e^+$
- 206 pb$^{-1}$ $e^-$

~ 1 fb$^{-1}$
Events with isolated e or \( \mu \) and \( P_T^{\text{miss}} \)

HERA I:
H1 observed 11 events at \( P_T^X > 25 \) GeV
at SM expectation 3.5±0.6

ZEUS in agreement with SM expectation

Both experiments performed search in complete HERA data set
Real W production in photoproduction with W decay into leptons
main process for this event topology
Hadronic system with typically low $p_T^X$

$\sigma_W \sim 1.3 \text{ pb}^{-1}$
W decay branching ratio into e or $\mu \sim 20\%$

Other signal processes:
CC W production $\sim 7\%$
Cabbibo-Parisi Z0 production $\sim 3\%$ (only e channel)

Modelled using EPVEC generator with NLO QCD correction:
Modifies cross section by $\sim 10\%$, reduces theoretical uncertainty to $\sim 15\%$
Background processes

**e: Neutral Current**

\[ e_{(k^e)} \rightarrow e_{(k^{-e})} \]

Real electron and fake \( P_T^{\text{miss}} \) from mismeasurement

**e,\( \mu \): Charged Current**

\[ e_{(k^e)} \rightarrow e_{(k^{-e})} \quad \nu_{(k^\nu)} \rightarrow \nu_{(k^{-\nu})} \]

Misidentified e or \( \mu \) and real \( P_T^{\text{miss}} \)

**\( \mu \): Lepton Pair Production**

\[ e_{(k^e)} \rightarrow e_{(k^{-e})} \quad \nu_{(k^\nu)} \rightarrow \nu_{(k^{-\nu})} \]

Real \( \mu \) and fake \( P_T^{\text{miss}} \) from mismeasurement
H1 isolated leptons

Excess at high $p_T^X$

Agreement with SM

<table>
<thead>
<tr>
<th>H1 HERA I+II</th>
<th>$p_T^X &gt; 25$ GeV</th>
<th>e channel</th>
<th>$p_T^X$ (GeV) e and $\mu$ channels</th>
<th>$p_T^X$ (GeV) e and $\mu$ channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+ p$ data (294 pb$^{-1}$)</td>
<td>11 / 4.7 ± 0.9 (75%)</td>
<td>21 / 8.9 ± 1.5 (80%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^- p$ data (184 pb$^{-1}$)</td>
<td>3 / 3.8 ± 0.6 (61%)</td>
<td>3 / 6.9 ± 1.0 (67%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ZEUS isolated leptons

$15^\circ < \theta_l < 120^\circ$

41 events observed in 492 pb$^{-1}$ of data

<table>
<thead>
<tr>
<th>HERA I+II Ptx&gt;25GeV</th>
<th>e channel Obs/exp(signal)</th>
<th>μ channel Obs/expt.(signal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e$^+$ data</td>
<td>3/3.9 ±0.5(81%)</td>
<td>3/3.6±0.5(81%)</td>
</tr>
<tr>
<td>e$^-$data</td>
<td>3/3.2±0.6(69%)</td>
<td>2/2.4±0.4(85%)</td>
</tr>
</tbody>
</table>

Good agreement between data and Standard Model for both data sets
No Excess seen at high $P_T^X$ as seen by H1
H1 and Zeus combined

87/92.7±11.2 events with isolated leptons and \( P_T \)\(_{\text{miss}} \) observed in 0.97fb\(^{-1}\)

<table>
<thead>
<tr>
<th>H1+ZEUS HERA I+II</th>
<th>e channel</th>
<th>( \mu ) channel</th>
<th>e and ( \mu ) channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_T^X &gt; 25 \text{ GeV} )</td>
<td>obs. / exp. (signal)</td>
<td>obs. / exp. (signal)</td>
<td>obs. / exp. (signal)</td>
</tr>
<tr>
<td>( e^+p ) data (0.58 fb(^{-1}))</td>
<td>12 / 7.4 ± 1.0 (70%)</td>
<td>11 / 7.2 ± 1.0 (85%)</td>
<td>23 / 14.6 ± 1.9 (81%)</td>
</tr>
<tr>
<td>( e^-p ) data (0.39 fb(^{-1}))</td>
<td>4 / 6.0 ± 0.8 (67%)</td>
<td>2 / 4.8 ± 0.7 (87%)</td>
<td>6 / 10.6 ± 1.4 (76%)</td>
</tr>
<tr>
<td>( e^+ + e^- ) data (0.97 fb(-1))</td>
<td>4/6.0 ± 0.8 (67%)</td>
<td>2/4.8 ± 0.7 (87%)</td>
<td>29/25.3 ± 3.2 (79%)</td>
</tr>
</tbody>
</table>

Excess in \( e^+ \) data has significance of 1.8 \( \sigma \) based on data of both experiments (2.9\( \sigma \) H1 data only)
Cross section measurements

H1 data only

\[ \sigma_{\text{IsoLep}} = \frac{N_d - N_{bg}^{MC}}{L \epsilon} \]

\[ \epsilon = \frac{N_{\text{rec}}^{MC}}{N_{\text{gen}}^{MC}} \]

<table>
<thead>
<tr>
<th>( \sigma_{\text{IsoLep}} ) (pb)</th>
<th>Measured±stat±sys</th>
<th>SM±thesys</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \int ]</td>
<td>0.24±0.05±0.05</td>
<td>0.26±0.04</td>
</tr>
</tbody>
</table>

branching ratio \( W \to e, \mu \approx 21\% \)
subtract \( Z^0 \) processes

<table>
<thead>
<tr>
<th>( \sigma_{W} ) (pb)</th>
<th>Measured±stat±sys</th>
<th>SM±thesys</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \int ]</td>
<td>1.23±0.25±0.22</td>
<td>1.31±0.20</td>
</tr>
</tbody>
</table>

Both measured cross sections are in good agreement with the SM
Measurement of W polarisation fraction

\[ F_+ = 1 - F_ - F_0 \]

right     left     longitudinal polarisation fraction

\[
\frac{dN}{d\cos \theta^*} \propto (1 - F_ - F_0) \cdot \frac{3}{8} (1 + \cos \theta^*)^2 \\
+ \frac{3}{4} F_0 \cdot (1 - \cos^2 \theta^*) \\
+ \frac{3}{8} F_- (1 - \cos \theta^*)^2 .
\]

Fit H1 measured cross section to \( dN/d\cos\theta^* \) and extract \( F_0 \) and \( F_- \) simultaneously
Good agreement with the SM found compatible with Single top production within $1\sigma$. 

Single parameter fit (other parameter at SM value)

<table>
<thead>
<tr>
<th></th>
<th>HERA I+II data</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_-$</td>
<td>$0.58 \pm 0.15\text{(stat)} \pm 0.12\text{(sys)}$</td>
<td>$0.61 \pm 0.01\text{(stat)}$</td>
</tr>
<tr>
<td>$F_0$</td>
<td>$0.15 \pm 0.21\text{(stat)} \pm 0.09\text{(sys)}$</td>
<td>$0.19 \pm 0.01\text{(stat)}$</td>
</tr>
</tbody>
</table>
Anomalous single top production

SM single top production $\sigma<1\text{fb}$

Top production via flavor changing NC in BSM
Candidate process for excess
But: same rate for $e^+$ and $e^-$

Search for FCNC based on isolated lepton events of HERAI+II
additional good top quark reconstruction and positive lepton charge requirement (if possible)

24 events selected, 26 events SM prediction

No significant signal found using multi variant analysis
previous (hera1) analysis also considered hadronic W decays
Limits on FCNC cross section derived using maximum likelihood:

\[ \sigma(ep\rightarrow etX) < 0.16 \quad (95\% \text{ CL}) \]

HERA 1 results:
H1: \( \sigma(ep\rightarrow etx) < 0.55 \text{ pb} \)
Zeus: \( \sigma(ep\rightarrow etX)<0.23 \text{ pb} \)

Upper bound on the anomalous coupling:
\[ \kappa_{\tau\nu\gamma} < 0.14 \]

New limit extends into region of phase space uncovered by other colliders
Isolated $\tau$ leptons + $p_T^{\text{miss}}$

**H1** $\tau + p_T^{\text{miss}}$ candidate with large $P_T^X$

- $P_T^{\text{miss}} = 59$ GeV
- $P_T = 14$ GeV
- $P_T^X = 51$ GeV

Look for events with $P_T^{\text{miss}}$ and a narrow hadronic jet in complete HERA data set

- 45% of $\tau$ decay into 1 charged particle ("1-prong-decay") giving a narrow, pencil like jet
- Main (and large!) background CC events with narrow jets
- Complementary results to those in electron and muon channel
- Enhanced $\tau$ production above SM predicted by some $R_\rho$ violating SUSY models
- HERA I data ZEUS observed 3 events over SM expectation $0.4 \pm 0.12$,
  2 events at $P_T^X > 25$ GeV, SM expectation $0.2 \pm 0.05$
τ results

20 events observed
Good agreement with the SM prediction for e^+ and e^- data set
Only 1 event at high P_T^X – in the e-p data!
Dominated by background processes – only 14% signal (other channels up to 85%)
Multi-Leptons

Search for topologies with 2 or 3 high $p_T$ leptons

$p_T^{1l}>10\text{GeV}$, $p_T^{2l}>5\text{GeV}$, $20^0<\theta<160^0$

Third lepton:
$E_e>5\text{GeV}$ or $p_T^\mu>2\text{GeV}$, $5<\theta<175$

ZEUS: $ee$, $eee$

H1: $ee$, $e\mu$, $\mu\mu$, $eee$, $e\mu\mu$
QED processes with multi-lepton final state

- $\gamma\gamma$ process dominant
- CC $W$ production (7%)
- Cabbibo-Parisi $Z^0$ production (~3%, only in electron channel)
2 lepton results

H1 Multi-lepton analysis  HERA I+II (459 pb$^{-1}$)

- **ee**
  - 446 events

- **$\mu\mu$**
  - 185 events

- **e$\mu$**
  - 201 events

**Overall good agreement with SM**
- **H1**: 3 ee events observed at $M>100$GeV (all hera1 e$^+p$ data)
- **ZEUS**: 2 ee event observed at $M>100$GeV
3 lepton event

- $\mu_1$ (P_T = 64 GeV)
- $\mu_2$ (P_T = 62 GeV)
- $\mu_2$ (P_T = 2.7 GeV)
- e (P_T = 64 GeV)
H1 3 lepton results

H1 Multi-lepton analysis HERA I+II (459 pb$^{-1}$)

Overall good agreement with SM

Data slightly exceed SM prediction at high mass

3 eee events
Observed in hera 1 e$^+$p

2 eμμ events observed in Hera 2 e$^+$p
Zeus 3 lepton results

![Graph showing data for ZEUS (prel.) with an estimated 478 pb⁻¹. The graph displays events at high mass with 2 events highlighted.](image-url)
Results on 2+3 leptons

H1 Multi-lepton analysis HERA I+II (459 pb$^{-1}$)

\[ e^+p \text{ (286 pb}^{-1}\text{) } \]
\[ \text{2+3 leptons} \]

\[ e^-p \text{ (173 pb}^{-1}\text{) } \]
\[ \text{2+3 leptons} \]

4 events with high $\Sigma P_T$
3 ee events with $M>100$ GeV
1 $e\mu\mu$ event with $M_{12}>100$ GeV
SM expectation $1.9\pm0.4$

ZEUS

3 events with high $\Sigma P_T$
SM expectation $1.58^{+0.16}_{-0.12}$
Search for resonances in mass spectra of multi lepton sample

Additional charge and \( P_T \) cut for \( ee, e\mu \) channel, \( P_T^{miss} \) cut for \( \tau \)

<table>
<thead>
<tr>
<th></th>
<th>Events ( M_{ll}&gt;65\text{GeV} )</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ee )</td>
<td>3</td>
<td>2.45±0.11</td>
</tr>
<tr>
<td>( e\mu )</td>
<td>1</td>
<td>4.17±0.44</td>
</tr>
<tr>
<td>( e\tau )</td>
<td>1</td>
<td>2.1±0.5</td>
</tr>
</tbody>
</table>
Limit on $H^{\pm\pm}$ cross section

Best sensitivity for $H^{\pm\pm}\rightarrow e\mu$: $\sigma_{H^{\pm\pm}\rightarrow e\mu} < 0.05 \text{pb}$
Limits on $H^{±±}$ mass

H1 sets most stringent limits on $M_H$ for $H^{±±}$ coupling to $e\mu$ and $e\tau$ at coupling of electromagnetic strength:

$$h_{e\mu}=0.3 \quad M_H>141 \text{ GeV}$$
$$h_{e\tau}=0.3 \quad M_H>112 \text{ GeV}$$
Leptoquarks at HERA

Leptoquarks: color triplet boson with leptonic and baryonic quantum number:
Fermion number: F=L+3B    F=2 (e+p)    F=0 (se+p)

Buchmüller-Rückl-Wyler (BRW) model: LQ classified into 14 types (7 vector, 7 scalar) depending on spin, isospin, chirality

LQ at HERA: single production from incoming particles

\[ \hat{s} \rightarrow \lambda_{eq} \quad \lambda_{e\bar{q}_j} \quad \ell \quad q_i \]

\[ \hat{u} \rightarrow \lambda_{e\bar{q}_i} \quad \lambda_{\bar{q}_j} \quad \ell \quad \bar{q}_i \]

- **s-channel** (resonant production)
  - \( M_{LQ} \approx (sx)^{1/2} \)
  - \( M_{LQ} \leq 300 \text{ GeV} \)

- **u-channel** (LQ exchange)
  - \( M_{LQ} > s^{1/2} \)
  - \( M_{LQ} > 300 \text{ GeV} \) Contact interaction region

LQ decay lepton flavor conserving (LFC): LQ\( \rightarrow eq, \nu q \)
  or lepton flavor violating (LFV): LQ\( \rightarrow \mu q, \tau q \)

H1 and ZEUS search for LQ in inclusive NC and CC event sample of 2004/05 data
Limits on 1st generation $M_{LQ}$

No enhancement
No evidence for LQ signal

At $\lambda \sim 0.3$ exclude $M_{LQ} > 276-304$ GeV
Heavy Leptoquarks

- Possible new interaction between e and q can modify DIS cross section at high $Q^2$ via virtual effects.
- Search for virtual LQ exchange using 4 fermion eeqq contact interaction method.
  -> report by P. Schleper in Alternatives.

Lower limits on $M_{LQ}/\lambda$ derived for all LQ:
$M_{LQ} >> 300$ excluded for all LQ for $\lambda \sim 1$. 
Comparison with LEP and Tevatron

- **LEP**: contact interaction (indirect constraints from $e^-e^+ \rightarrow q\bar{q}$)
- **TEVATRON**: pair production ($\lambda$ independent)
- **HERA**: single production ($M_{LQ} < 300$ GeV) and contact interaction ($M_{LQ} > 300$ GeV)

~ factor 2 more lumi to be added using full HERA II data
Limits on LFV Leptoquarks

Typical selection:
Back-to-back topology, 
$P_T^{\text{calo}}>20\text{GeV}$

Assume:
No evidence for
Signal found

Exclude $M_{LQ}>300 \text{ GeV}$ for $\lambda \sim 0.3$
Summary

• Results for isolated leptons with $p_T^{\text{miss}}$ shown for complete HERA data sample and for the first time with $\text{H1}+\text{ZEUS}$ combination $\sim1\text{fb}^{-1}$:
  – In $e+p$ data: H1 observed 21 events where 8.9 were expected in complete data and even stronger signal in $e+p$ data
  – ZEUS observed 6 events where 7.4 expected

• All HERA data analysed by H1 and ZEUS multi-lepton events
  – At high $\Sigma P_T$ H1 observes 4 events, expectation is $1.9\pm0.4$
    ZEUS observes 3 events, expectation is $1.58^{+0.12}_{-0.16}$
  – Combined results expected soon

• Limits for LQ updated – improvement with full HERA data sample to come
extras
## Isolated lepton event selection

<table>
<thead>
<tr>
<th>Variable</th>
<th>Electron</th>
<th>Muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{_l}$</td>
<td>$5^\circ &lt; \theta_{<em>l} &lt; 140^\circ$ (H1), $15^\circ &lt; \theta</em>{_l} &lt; 120^\circ$ (ZEUS)</td>
<td></td>
</tr>
<tr>
<td>$P_T^{_l}$</td>
<td>&gt; 10 GeV</td>
<td></td>
</tr>
<tr>
<td>$P_T^{_{calo}}$</td>
<td>&gt; 12 GeV</td>
<td></td>
</tr>
<tr>
<td>$P_T^{_{miss}}$</td>
<td>&gt; 12 GeV</td>
<td></td>
</tr>
<tr>
<td>$P_X^{_l}$</td>
<td>-</td>
<td>&gt; 12 GeV</td>
</tr>
<tr>
<td>$D_{jet}$</td>
<td></td>
<td>&gt; 1.0</td>
</tr>
<tr>
<td>$D_{track}$</td>
<td>&gt; 0.5 for $\theta_{_e} \geq 45^\circ$</td>
<td></td>
</tr>
<tr>
<td>$\zeta_{_{q1}}$</td>
<td>&gt; 5000 GeV$^2$ for $P_T^{_{calo}} &lt; 25$ GeV</td>
<td></td>
</tr>
<tr>
<td>$V_{ap}/V_p$</td>
<td>&lt; 0.5 ($&lt; 0.15$ for $P_T^{_e} &lt; 25$ GeV)</td>
<td>&lt; 0.5 ($&lt; 0.15$ for $P_T^{_{calo}} &lt; 25$ GeV)</td>
</tr>
<tr>
<td>$\Delta\phi_{_{l-X}}$</td>
<td>&lt; 160$^\circ$</td>
<td>&lt; 170$^\circ$</td>
</tr>
<tr>
<td>$\delta_{_{miss}}$</td>
<td>&gt; 5 GeV**</td>
<td></td>
</tr>
<tr>
<td># isolated $\mu$</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

*H1: only if one $e$ candidate is detected, with the same charge as the beam lepton*
Multi-lepton event yields at $M_{ll}>100\text{GeV}$

H1 preliminary HERA I+II

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>SM</th>
<th>Pair Production</th>
<th>NC-DIS + Compton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee\ M_{ll}&gt;100\text{GeV}$</td>
<td>3</td>
<td>1.0 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>$\mu\mu\ M_{ll}&gt;100\text{GeV}$</td>
<td>0</td>
<td>0.06 ± 0.03</td>
<td>0.06 ± 0.03</td>
<td>—</td>
</tr>
<tr>
<td>$e\mu\ M_{ll}&gt;100\text{GeV}$</td>
<td>1</td>
<td>0.53 ± 0.05</td>
<td>0.53 ± 0.05</td>
<td>—</td>
</tr>
<tr>
<td>$e\mu\ M_{ll}&gt;100\text{GeV}$</td>
<td>3</td>
<td>0.6 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>—</td>
</tr>
<tr>
<td>$e\mu\ M_{ll}&gt;100\text{GeV}$</td>
<td>1</td>
<td>0.04 ± 0.02</td>
<td>0.04 ± 0.02</td>
<td>—</td>
</tr>
<tr>
<td>$e\mu\ M_{ll}&gt;100\text{GeV}$</td>
<td>1</td>
<td>0.007 ± 0.005</td>
<td>0.007 ± 0.005</td>
<td>—</td>
</tr>
</tbody>
</table>

ZEUS preliminary HERA I+II

<table>
<thead>
<tr>
<th>Type</th>
<th>DATA</th>
<th>DATA</th>
<th>SM</th>
<th>Pair production</th>
<th>QEDC</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+p</td>
<td>2e</td>
<td>1</td>
<td>0.5±0.1</td>
<td>0.5±0.1</td>
<td>0.4±0.1</td>
<td>0.07±0.03</td>
</tr>
<tr>
<td></td>
<td>3e</td>
<td>2</td>
<td>0.6±0.07±0.5</td>
<td>0.6±0.07</td>
<td>&lt;0.01</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>e−p</td>
<td>2e</td>
<td>1</td>
<td>0.0±0.1</td>
<td>0.4±0.04</td>
<td>0.39±0.3</td>
<td>0.04±0.01</td>
</tr>
<tr>
<td></td>
<td>3e</td>
<td>0</td>
<td>0.4±0.1±0.5</td>
<td>1.0±0.1</td>
<td>&lt;0.01</td>
<td>&lt;0.5</td>
</tr>
</tbody>
</table>
2 lepton mass spectra, $H^{±±}$ search (backup)

H1 HERA I data, $H^{±±}$ preselection

6 evts obs.
0.53±0.06 expt.

1 event after final selection (charge+ $P_T$ cuts)
Leptoquark search all mass spectra

![Graphs showing events vs. M_{LQ} for NC and CC processes with different polarization and SM uncertainty.](image-url)
$H^±±$ production

H1 HERA I data
CC and NC cross section

\[ \frac{d\sigma}{dQ^2} (\text{pb}/\text{GeV}^2) \]

HERA II

\[ y < 0.9 \]
\[ P_T = 0 \]