Multi-lepton production at HERA
-Using ZEUS detector

University of Tokyo
Nao Okazaki
**Hadron Electron Ring Accelerator**

**HERA**

**HERA** is the only electron-proton collider in the world.

**large center of mass energy**

**Center of mass energy**

\[
\begin{align*}
\text{e} & \quad 318 \text{ GeV} \\
27.5 \text{ GeV} & \quad 920 \text{ GeV}
\end{align*}
\]
Multi-lepton production at HERA

- Multi-lepton production in $e^\pm p$ collision proceeds dominantly via Bethe-Heitler process.

- At HERA, we can explore up to a large invariant mass, $\sim 150$ GeV.

  - May be sensitive to new physics.
**H1 reported an excess in HERA I data**

- Using 115 $pb^{-1}$ HERA I data

### Graphs

- **H1 Data 115 pb$^{-1}$**
- **Pair Production (GRAPE)**
- **DIS**
- **DIS + Compton**

### Table

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>SM</th>
<th>Pair Production (GRAPE)</th>
<th>DIS + Compton</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘2e’ $M_{12} &gt; 100$ GeV</td>
<td>3</td>
<td>$0.30 \pm 0.04$</td>
<td>$0.21 \pm 0.03$</td>
<td>$0.09 \pm 0.02$</td>
</tr>
<tr>
<td>‘3e’ $M_{12} &gt; 100$ GeV</td>
<td>3</td>
<td>$0.23 \pm 0.04$</td>
<td>$0.23 \pm 0.03$</td>
<td>$&lt; 0.02 (95% C.L.)$</td>
</tr>
</tbody>
</table>

In ZEUS analysis

- Using HERA I, II data.
- Multi-electron and di-tau productions are searched for.

**Multi-electron**

- HERA II (2003-05)
  - 121 $pb^{-1}$ $e^\pm p$ run
  - 175 $pb^{-1}$ $e^\pm p$ run

Total
- 296 $pb^{-1}$

**Di-tau**

Data: HERA II (2005)
- 135 $pb^{-1}$ $e^- p$ run

Running period:
- HERA I 1992-2000
- HERA II 2003-2006
- Luminosity upgrade
  - Longitudinally polarized lepton beam
Multi-electrons
**Event topology ; e,e,(e)**

**Signal:** (simulated by GRAPE)
- Electrons from pair production and a scattered electron.
- One electron is often out of detector acceptance.

**Background:**
- **Neutral Current Deep Inelastic Scattering (NC DIS)** (simulated by DJANGO)
  - For example, $\pi^0$ in jets is misidentified as an electron.
- **QED Compton (QEDC)** (simulated by COMPTON 2.0)
  - For example, a photon is misidentified as an electron

*Multi-electron (1/7)*
Event selection

◆ 2 or more isolated electromagnetic (EM) clusters in the calorimeter.

◆ At least 2 EM clusters are within the Central Tracking region and are associated with a track of CTD.

◆ Highest Pt electron, $P_T,1 > 10 \text{GeV}$

◆ Second highest Pt electron, $P_T,2 > 5 \text{GeV}$

◆ Z position of the primary vertex, $|Z_{\text{vertex}}| < 50 \text{cm}$

*Multi-electron (2/7)*
Final sample distribution \((P_{T}^{e} \text{ and } \theta_{e}^{e})\)

**ZEUS**

Data is in good agreement with MC.

**Highest Pt electron**

**Second highest Pt electron**

*Multi-electron (3/7)*
The SM gives a good description of the measurements.
One event is found at $M_{1,2} > 100$ GeV.
## Event yields at large $M_{1,2}$

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>SM total</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^{\pm}296 \text{pb}^{-1}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2e $M_{1,2} &gt; 50 \text{GeV}$</td>
<td>53</td>
<td>67 $\pm$ 7.1</td>
<td>19 $\pm$ 2.6</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.5 $\pm$ 0.5</td>
<td>0.6 $\pm$ 0.3</td>
</tr>
<tr>
<td>3e $M_{1,2} &gt; 50 \text{GeV}$</td>
<td>12</td>
<td>15 $\pm$ 1.3</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.8$^{+0.3}_{-0.04}$</td>
<td>&lt; 0.4</td>
</tr>
</tbody>
</table>

The measured event yields agree with the SM predictions.
Event displays

The highest $M_{12}$ event of the 2e event.

$M_{1,2} = 123 \text{GeV}$

$Pt_1^e = 55 \text{GeV}, \quad Pt_2^e = 54 \text{GeV}$

Multi-electron (6/7)
The highest $M_{12}$ event of the 3e event.

$M_{1,2} = 103\text{GeV}$

$Pt_{1}^{e} = 62\text{GeV}$

$Pt_{2}^{e} = 47\text{GeV}$

$Pt_{3}^{e} = 35\text{GeV}$

Multi-electron (7/7)
Di-tau
**Event topology ; e, μ**

**Signal:**
In this analysis, events in which one tau decays to an electron and the other decays to a muon are searched for.

\[
\begin{align*}
\tau &\rightarrow e, \nu_e, \nu_\tau \\
\tau &\rightarrow \mu, \nu_\mu, \nu_\tau
\end{align*}
\]

**Background:**
**Di-muon** events in which one muon escapes detection, for example, by passing through beam pipe.

*Di-tau (1/10)*
Event selection

◆ The proton is scattered elastically.
  • Energy deposit around beam pipe < 1GeV
  • 0 < Number of tracks < 4

◆ To be with one muon and one or more electrons.
  
  **Electron identification:**
  • Energy > 4GeV
  • $\theta_e < 2.6$ rad

  **Muon identification:**
  • By combined information from the muon detectors, the calorimeters, the tracking detectors.
  • $Pt > 2 \ GeV$

-MC expectation-

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>4.1</td>
<td>events</td>
</tr>
<tr>
<td>Di-muon background</td>
<td>15.7</td>
<td>events</td>
</tr>
</tbody>
</table>

Di-tau (2/10)

Need further di-muon background rejection
Background rejection

\[ E^{-P_z} = (E^{-P_z})_{\text{CAL}} + (E^{-P_z})_{\text{Muon}} < 45 \text{ GeV} \]

E-Pz is conserved to be 55 GeV (\(2E^\text{beam}_e\)) unless particles escape in \(-z\) direction.

Because a scattered electron often escapes to \(-z\) direction in di-tau events, E-Pz becomes lower.

On the other hand as the electron in di-muon events must be a scattered electron, E-Pz peaks at 55GeV.
Background rejection (cont’d)

There is no extra muon candidates found by loosen selection criteria.

For example, a calorimeter energy deposit which is consistent with a Minimum Ionizing Particle (MIP).

-MC expectation-

<p>| | | |</p>
<table>
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<tbody>
<tr>
<td>Signal</td>
<td>4.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Di-muon background</td>
<td>15.7</td>
<td>&lt;0.2</td>
</tr>
</tbody>
</table>
## Results

### Event yields

<table>
<thead>
<tr>
<th>Data</th>
<th>$2\tau$ (Signal)</th>
<th>$2\mu$ (Background)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$e^{-135pb^{-1}}$</td>
</tr>
<tr>
<td>3</td>
<td>$2.0 \pm 0.8$</td>
<td>$&lt; 0.2$</td>
</tr>
</tbody>
</table>

- 3 Events are found
- Event yield is consistent with the SM.
Event displays

$M_{e,\mu} = 9.8\text{GeV}$

$P_{t_e} = 3.5\text{GeV}$,

$P_{t_\mu} = 4.9\text{GeV}$

Di-tau (6/10)
\[ M_{e,\mu} = 15.7\text{GeV} \]
\[ P_{t_e} = 12.6\text{GeV}, \]
\[ P_{t_{\mu}} = 4.8\text{GeV} \]
$M_{e,\mu} = 5.8\text{GeV}$
$P_{t e} = 1.4\text{GeV}$
$P_{t \mu} = 4.2\text{GeV}$

*Di-tau (8/10)*
Final sample distributions ($P_{T_l}$ and $\theta_l$)

Data is compatible with the SM prediction.

Di-tau(9/10)
Missing $\text{Pt, } M_{e, \mu}$

Data is compatible with MC.

Di-tau (10/10)
Summary

◆ Multi-electron production has been studied by using 296 \( pb^{-1} \) of the HERA I and II e\( ^\pm \)p data.
  • One event is found for \( M_{1,2} > 100 \) GeV in 2e and 3e sample.
  • No excess is observed.

◆ The di-tau production has been studied by using 135 \( pb^{-1} \) of the HERA II e\( ^- \)p data.
  • 3 events are found.

◆ The measured event yields are found to be in agreement with the predictions from the SM.
Backup slides
Overview (y-z plane)

Tracking detectors
Calorimeters
Muon detectors

[FCAL inner ring]

The tracking detectors
Data sample

Multi-electron
Data; HERA I (1996-2000) \(17\text{pb}^{-1}\) \(e^- p\) run
\(104\text{pb}^{-1}\) \(e^+ p\) run

HERA II (2003-05) \(135\text{pb}^{-1}\) \(e^- p\) run
\(40\text{pb}^{-1}\) \(e^+ p\) run

Total \(296\text{pb}^{-1}\)

Di-tau
Data; HERA II (2005) \(135\text{pb}^{-1}\) \(e^- p\) run

High statistics data is used
**Multi-electron analysis at ZEUS**

**Electron identification:**
- To be found by an algorithm which combined information from the calorimeter and the tracking detector.
- Energy not associated with electron in an $\eta \cdot \phi$ cone of radius 0.8 < 0.3 GeV

- *Forward* ($\theta_e < 17^\circ$) $\quad$ Energy > 10 GeV
- *Central* ($17^\circ < \theta_e < 164^\circ$) $\quad$ Energy > 10 GeV
  
  *[CentralTrackingDetector region]*

- *Rear* ($\theta_e > 164^\circ$) $\quad$ Energy > 5 GeV

For central region:

- DCA between the CAL energy deposit and the track < 8 cm
- Number of tracks except the matching track in an $\eta \cdot \phi$ cone of radius 0.4 = 0

\[
R = (\Delta \eta^2 + \Delta \phi^2)^{\frac{1}{2}}
\]

\[
\eta = -\ln(\tan \frac{\theta}{2})
\]
Multi-electron analysis at ZEUS (cont’d)

**Systematic uncertainly**

◆ The energy scale varied conservatively by ±2% for the calorimeters.

<table>
<thead>
<tr>
<th></th>
<th>2e</th>
<th>3e</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.4%(+2%)</td>
<td>5.8%(+2%)</td>
</tr>
</tbody>
</table>

**Background**

<table>
<thead>
<tr>
<th></th>
<th>Total background</th>
<th>QED Compton</th>
<th>NC DIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2e</td>
<td>26.0%</td>
<td>10.7%</td>
<td>15.2%</td>
</tr>
<tr>
<td>3e</td>
<td>1.0%</td>
<td>0.27%</td>
<td>1.2%</td>
</tr>
<tr>
<td>Total</td>
<td>23%</td>
<td>9.4%</td>
<td>13.4%</td>
</tr>
</tbody>
</table>
Multi-electron analysis at ZEUS (cont’d)

Event displays

The highest Pt electron:
[Theta] 1.2 rad  
[Charge] positive

The 2nd highest Pt electron:
[Theta] 0.5 rad  
[Charge] negative

The 3rd highest Pt electron:
[Theta] 0.58 rad  
[Charge] positive
Multi-electron analysis at ZEUS (cont’d)

Distributions of $P_T$ and $\theta$ in 3e sample
Multi-electron analysis at H1

The cross section integrated over the phase space defined above.

\[ \sigma = (0.59 \pm 0.08 \pm 0.05) \text{pb} \]
**Tau pair production at H1**

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Leptonic $e$</th>
<th>Semi leptonic $e \tau$ jet</th>
<th>Semi leptonic $\mu \tau$ jet</th>
<th>Hadronic $\tau$ jet $\tau$ jet</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 Data</td>
<td>7</td>
<td>2</td>
<td>10</td>
<td>11</td>
<td>30</td>
</tr>
<tr>
<td>SM</td>
<td>2.9 – 0.4</td>
<td>6.3 – 0.9</td>
<td>7.0 – 1.3</td>
<td>11.0 – 2.0</td>
<td>27.1 – 4.1</td>
</tr>
<tr>
<td>$\tau^+ \tau^-$</td>
<td>56%</td>
<td>47%</td>
<td>85%</td>
<td>50%</td>
<td>59%</td>
</tr>
</tbody>
</table>

*hep-ex/0604022
accepted by Eur.Phys.J.C
**Di-tau analysis at ZEUS**

**Event selection**

**Trigger:** with muon candidates found by the muon detectors. \( |Z_{\text{vertex}}| < 50 \text{cm} \)

**Vertex:** \( (X_{\text{vertex}} - 1.33)^2 + (Y_{\text{vertex}} - 0.22)^{2.2} < 1.5 \text{cm} \)

**Muon candidates definition**

- \( \text{Pt} > 2 \text{GeV} \)
- To match with track

**Electron candidates definition**

- \( \theta < 2.6 \text{rad} \)
  - For central region \( 0.3 < \theta_e < 2.6 \text{ rad} \)
  - Momentum of track \( \geq 2 \text{ GeV} \)
  - DCA < 10 cm

- Energy > 4GeV
- Energy in cone not from an electron candidate < 5GeV

◆ Events are required to have one or more muons and one or more electrons

◆ Number of good tracks = 1, 2, 3

(Pt of track > \(0.15 \text{GeV} \), inner layer < 2, outer layer > 2)

If there are more than 1 track, at least a track is required to match an electron

◆ FCAL 1nd + 2nd inner ring energy < 1GeV
**Di-tau analysis at ZEUS (cont’d)**

**Event selection (cont’d)**

- Number of muons = 1.
  \( \text{Pt} > 1.5 \) or momentum > 1.5 GeV

- 0.1 < colinearity < 2.7 (rad)

- \( E - P_z < 45 \text{ GeV} \)

- There is no calorimeter energy deposit which is consistent MIP.

Not to be CAL noise. Not match above electron candidates and a muon candidates. 0.2 < Energy of EMC < 1.5 GeV and 0.5 < Energy of HAC < 2.5 GeV.

- \( \theta_e < 1.0 \text{ rad} \) if there are electron candidates which have negative charge.

![Graph](image-url)
Di-tau final samples

<table>
<thead>
<tr>
<th>Nmu</th>
<th>Emncand</th>
<th>Muqual</th>
<th>Mupt</th>
<th>Muth</th>
<th>Muph</th>
<th>Mucharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>4</td>
<td>4.86</td>
<td>1.41</td>
<td>0.033</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>4.78</td>
<td>2.04</td>
<td>3.46</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.38</td>
<td>0.71</td>
<td>2.92</td>
<td>1</td>
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<tbody>
<tr>
<td>12.88</td>
<td>1.75</td>
<td>0.34</td>
<td>1</td>
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<th>Muph</th>
<th>Mucharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.56</td>
<td>0.26</td>
<td>0.083</td>
<td>1</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>