“Search for multi-lepton events with the ZEUS detector at HERA”

and

“VCMVD: an algorithm for MVD tracking at TLT”

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Tutore: Dott. Luca Stanco

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Outline – Part I

- The experimental setup
- Introduction and motivations
- Multi-electron events search
- Di-muon events search
HERA is a particle accelerator located in Hamburg...

...and collides $e^\pm p$ at $\sqrt{s} = 300/318$ GeV:

- $E_e = 820$ (920) GeV
- $E_p = 27.5$ GeV

In 1992-2000 HERA supplied the following integrated luminosity:

<table>
<thead>
<tr>
<th>Years</th>
<th>Lumi [pb$^{-1}$]</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992-94</td>
<td>2.19</td>
<td>$e^- p$</td>
</tr>
<tr>
<td>1994-97</td>
<td>70.92</td>
<td>$e^+ p$</td>
</tr>
<tr>
<td>1998-99</td>
<td>25.20</td>
<td>$e^- p$</td>
</tr>
<tr>
<td>1999-00</td>
<td>94.95</td>
<td>$e^+ p$</td>
</tr>
</tbody>
</table>

- In 1998 $\sqrt{s}$ was raised from 300 GeV to 318 GeV.
The HERA Collider

HERA kinematics:

- Centre-of-mass energy:
  \[ s = (P + k)^2. \]
- Transferred 4-momentum, squared:
  \[ Q^2 = -(k - k')^2. \]
- Bjorken-\(x\):
  \[ x = Q^2/(2P \cdot q). \]
- Inelasticity:
  \[ y = (P \cdot q)/(P \cdot k). \]
- Proton-photon mass, squared:
  \[ W^2 = (P + q)^2. \]

Electron-Proton scattering

- Neutral Current: \(ep \rightarrow eX\)
- Charged Current: \(ep \rightarrow \nu X\)

Multi-leptons at HERA – MVD tracking at ZEUS TLT – p.4/92
ZEUS is a general purpose detector:

The components used in the analyses are:

- Central Tracking Detector (CTD),
- Uranium Calorimeter (CAL),
- Muon Chambers (B/RMUON + FMUON),
- Luminosity Monitor.
Di-lepton production at HERA

Lepton pair production is a pure QED process, well predictable in the Standard Model (SM) context.

- Main contribution: Bethe-Heitler (BH) process.
- Other contributions: Cabibbo-Parisi (CP) and Drell-Yan (DY).

Feynmann diagrams:
Backgrounds

- Vector meson decays: $\Upsilon \rightarrow l^+ l^-$ (BR $\sim$ 1-2%).
- Single lepton production:
  - Heavy quark decays: $q \rightarrow q' W^* \rightarrow q' l \nu$;
  - $W$-production;
  - $\tau$ decays.
- Backgrounds to multi-electron search: processes where hadrons or photons are misidentified as electrons:
  - Neutral Current DIS;
  - QED-Compton.
Motivations

- Test QED & photon spectrum of the proton.
- Cross-check H1 excesses:

High Mass multi-electrons at H1:

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2e$, $M_{12} &gt; 100$ GeV</td>
<td>3 evts</td>
<td>$0.30 \pm 0.04$</td>
</tr>
<tr>
<td>$3e$, $M_{12} &gt; 100$ GeV (see hep-ex/0307015)</td>
<td>3 evts</td>
<td>$0.23 \pm 0.04$</td>
</tr>
</tbody>
</table>

Isolated leptons with $p_T$:

Combined Electron and Muon

<table>
<thead>
<tr>
<th>Type</th>
<th>Data</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+p$</td>
<td>$10e$</td>
<td>$9.9 \pm 1.3$</td>
</tr>
<tr>
<td></td>
<td>$8\mu$</td>
<td>$2.56 \pm 0.44$</td>
</tr>
<tr>
<td>$e^-p$</td>
<td>$1e$</td>
<td>$1.69 \pm 0.22$</td>
</tr>
<tr>
<td></td>
<td>$0\mu$</td>
<td>$0.37 \pm 0.06$</td>
</tr>
</tbody>
</table>

(see Phys. Lett. B561, 241)
Multi-electron search
Event Selection

Electron selection

- EM electron finder (CTD+CAL info);
- Isolation cuts:
  - $E_{\text{cone}} < 0.3 \text{ GeV in R=0.3 (}\eta\phi\text{)},$
  - $N_{\text{Trk}} = 0 \text{ in R=0.4 (}\eta\phi\text{)}$;
- $E_e > 10 \text{ GeV (}\theta \leq 164^\circ\text{)} \text{ OR } E_e > 5 \text{ GeV (}\theta > 164^\circ\text{)}.$

Event Selection

- Vertex: $|z| < 50 \text{ cm};$
- two electrons in $17^\circ < \theta < 164^\circ;$
- $E_T^{e1} > 10 \text{ GeV};$
- $E_T^{e2} > 5 \text{ GeV}.$

→ Two classes: “2e” (2 electrons) and “3e” (3 electrons) events.

Preselection

Fast selection and reduction of data. Selection criteria:

- Trigger selection: di-electron OR NC-DIS OR High-$E_T$;
- No. of CTD tracks: $1 \leq N_{\text{TrkVtx}} \leq 9$;
- Transverse momentum in CTD: $\sum_i P_{T,i} > 3 \text{ GeV}.$
Data to MC comparison

1996-2000 data taking \( \rightarrow \) \( L=120.49 \ \text{pb}^{-1} \)

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>All SM</th>
<th>di-ele MC</th>
<th>NC-DIS MC</th>
<th>QED-C MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>All ( 2e+3e )</td>
<td>209</td>
<td>235.82</td>
<td>207.00</td>
<td>18.72</td>
<td>10.10</td>
</tr>
<tr>
<td>( M_{12} &gt; 50 \ \text{GeV} )</td>
<td>23</td>
<td>35.01</td>
<td>30.14</td>
<td>3.40</td>
<td>1.47</td>
</tr>
<tr>
<td>( M_{12} &gt; 100 \ \text{GeV} )</td>
<td>1</td>
<td>1.12</td>
<td>0.91</td>
<td>0.08</td>
<td>0.13</td>
</tr>
</tbody>
</table>

\( E - P_z \) permits to separate Bkg from signal.

Monte Carlo describes data reasonably well.
Cross section: sample selection

A clean $ep \rightarrow eeX$ sample is needed for cross section measurement.

“$\gamma\gamma$” selection

- 2 electrons in $17^\circ < \theta < 164^\circ$;
- $E_{T}^{e1} > 10$ GeV and $E_{T}^{e2} > 5$ GeV;
- $M_{12} > 5$ GeV;
- $E - P_{z} < 45$ GeV (cuts NC-DIS and QED-C).

Results

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>All SM</th>
<th>di-ele MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>All $\gamma\gamma$</td>
<td>51</td>
<td>52.86</td>
<td>52.71</td>
</tr>
<tr>
<td>$M_{12} &gt; 50$ GeV</td>
<td>3</td>
<td>2.88</td>
<td>2.80</td>
</tr>
<tr>
<td>$M_{12} &gt; 100$ GeV</td>
<td>0</td>
<td>0.09</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Nice agreement of data and MC.
## Total cross section

<table>
<thead>
<tr>
<th>Period</th>
<th>Purity</th>
<th>Acceptance</th>
<th>$\sigma_{\text{DATA}}$ (pb)</th>
<th>$\sigma_{\text{MC}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996-97</td>
<td>0.825</td>
<td>0.234</td>
<td>$1.66 \pm 0.43^{+0.18}_{-0.14}$</td>
<td>1.55</td>
</tr>
<tr>
<td>1998-99</td>
<td>0.773</td>
<td>0.292</td>
<td>$0.82 \pm 0.41^{+0.13}_{-0.12}$</td>
<td>1.66</td>
</tr>
<tr>
<td>1999-00</td>
<td>0.790</td>
<td>0.283</td>
<td>$1.73 \pm 0.31^{+0.22}_{-0.17}$</td>
<td>1.66</td>
</tr>
<tr>
<td>1996-00</td>
<td></td>
<td></td>
<td>$1.62 \pm 0.23^{+0.21}_{-0.16}$</td>
<td></td>
</tr>
</tbody>
</table>

- **1996-97**: cross-section is measured at $\sqrt{s} = 300$ GeV.
- **1996-00**: cross-section is referred to $\sqrt{s} = 318$ GeV.
- First uncertainty is **statistical**, second is **systematic**.
- Main systematics: CAL energy scale simulation ($^{+9.4}_{-4.1}$%), isolation cut ($+7.3$%).
Differential cross section

\begin{align*}
\frac{d\sigma}{dM_{12}} & (\text{pb}/\text{GeV}) \\
\frac{d\sigma}{dP_{T}^{e}} & (\text{pb}/\text{GeV}) \\
\frac{d\sigma}{d\theta_{e}} & (\text{pb}/\text{rad})
\end{align*}

\text{ZEUS 1996-00 GRAPE MC}
Discussion

- Multi-electron events sought in ZEUS 1996-2000 data.
- Data distributions compared to SM: good description.
- The excess found by H1 is not confirmed.
- Total and differential cross sections were measured: agreement with SM in shape and normalisation.
- Outlook: reduce systematic uncertainties, analyse 1994-95.

Phase space

- 2 electrons in $17^\circ < \theta < 164^\circ$
- $E_{T}^{e1} > 10 \text{ GeV}$ and $E_{T}^{e2} > 5 \text{ GeV}$
- $M_{12} > 5 \text{ GeV}$
- $E - P_z < 45 \text{ GeV}$

Total cross section

$$\sigma(ep \rightarrow eeeX) = 1.62 \pm 0.23^{+0.21}_{-0.16} \text{ pb}$$

$$\sigma_{MC} = 1.66 \text{ pb}$$
Di-muon search
Event Selection

Preselection
Fast selection and reduction of data. Selection criteria:

- Trigger selection: B/RMUON activity OR FMUON activity;
- No. of CTD tracks: $2 \leq N_{TrkVtx} \leq 7$;
- Transverse momentum in CTD: $\sum_i P_{T,i} > 1.5$ GeV.

Muon selection

- Muon finding:
  - GLOMU: CTD + CAL + B/RMUI,
  - MPMATCH2: CTD + FMUON,
  - CTD + CAL (MIPs);
- Isolation cut: $D^\mu_{Trk} > 1$ in $\eta\phi$;
- $P_T > 5$ GeV.

Event Selection

- Vertex: $|z| < 50$ cm AND $\sqrt{x^2 + y^2} < 0.5$ cm;
- 2 muons (1 matched to chambers);
- Cosmic muons rejection:
  - acollinearity: $\cos \Omega > -0.995$,
  - timing cut.
Backgrounds (γ, heavy quarks and τ decays) were analysed by H1: found to be negligible.

In my analysis they were neglected.
Comparison of data to MC

1996-2000 data taking \( \rightarrow L=101.47\text{pb}^{-1} \)

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>di-mu MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>218</td>
<td>241.14</td>
</tr>
<tr>
<td>( M_{\mu\mu} &gt; 50 \text{ GeV} )</td>
<td>6</td>
<td>3.91</td>
</tr>
<tr>
<td>( M_{\mu\mu} &gt; 100 \text{ GeV} )</td>
<td>0</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Three di-muons crowd at \( M_{\mu\mu} \approx 50 \text{ GeV} \): genuine events.

Monte Carlo describes data reasonably well.
### Total cross section

<table>
<thead>
<tr>
<th>Period</th>
<th>Purity</th>
<th>Acceptance</th>
<th>$\sigma_{\text{DATA}}$ (pb)</th>
<th>$\sigma_{\text{MC}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996-97</td>
<td>0.953</td>
<td>0.436</td>
<td>$4.65 \pm 0.56^{+0.35}_{-0.31}$</td>
<td>5.31</td>
</tr>
<tr>
<td>1998-99</td>
<td>0.956</td>
<td>0.438</td>
<td>$4.97 \pm 0.98^{+0.29}_{-0.27}$</td>
<td>5.21</td>
</tr>
<tr>
<td>1999-00</td>
<td>0.968</td>
<td>0.427</td>
<td>$4.81 \pm 0.45^{+0.35}_{-0.33}$</td>
<td>5.32</td>
</tr>
<tr>
<td>1996-00</td>
<td></td>
<td></td>
<td>$4.79 \pm 0.33^{+0.35}_{-0.32}$</td>
<td></td>
</tr>
</tbody>
</table>

- **1996-97**: cross-section is measured at $\sqrt{s} = 300$ GeV.
- **1996-00**: cross-section is referred to $\sqrt{s} = 318$ GeV.
- **First uncertainty is statistical**, second is **systematic**.
- **Main systematics**: muon chamber eff. ($^{+5.4}_{-4.8}$%), isolation cut (+4.0%).

Multi-leptons at HERA – MVD tracking at ZEUS TLT – p.20/92
Differential cross section

Multi-leptons at HERA – MVD tracking at ZEUS TLT – p.21/92
Discussion

- Di-muon events sought in ZEUS 1996-2000 data.
- Data distributions compared to SM: good description.
- 3 events found at $M_{\mu\mu} \sim 50$ GeV: genuine di-muons.
- Total and differential cross section were measured: agreement with SM in shape and normalisation.
- Outlook: reduce systematic uncertainties, analyse background ($\bar{b}b, c\bar{c}, \Upsilon, \tau$ decays).

Phase space

- 2 muons in $15^\circ < \theta < 164^\circ$
- $P_T^\mu > 5$ GeV
- $M_{\mu\mu} > 5$ GeV

Total cross section

$$\sigma(ep \rightarrow e\mu\mu X) = 4.79 \pm 0.33^{+0.35}_{-0.32} \text{ pb}$$

$$\sigma_{MC} = 5.32 \text{ pb}$$
VCMVD: MVD tracking at ZEUS
Third Level Trigger
Outline – Part II

- Introduction and motivations
- The ZEUS Micro-Vertex Detector (MVD)
- Description of the method
- Results
- Discussion
Internal detectors are plunged in a magnetic field: charged particles follow helix-like trajectories.

Helices are characterised by 5 parameters $a_i$ and a reference point $(x_0, y_0)$:

- $a_1 = \phi_H$: azimuthal angle at $s = 0$;
- $a_2 = Q/R$: helix curvature;
- $a_3 = Q D_H$: closest approach to $(x_0, y_0)$;
- $a_4 = Z_H$: $z$ coordinate at $s = 0$;
- $a_5 = \cot \theta$: $\theta$ is the polar angle at $s = 0$.
MVD: motivations

\( F^\text{charm}_2 \) measurement  Photoproduction of jets  Exotic processes

- **MVD will allow better charm tagging** (higher efficiency and larger kinematical range).
- Measurement of \( F^\text{charm}_2 \) and gluon density.
- **MVD will allow better tagging** of resolved and direct charm/beauty photoproduction and thus better event selection and cross-section measurement.
- **Heavy states are boosted forward.**
- **daughters’ decay lengths may be detected even if particles are short-lived.**
VCMVD: motivations

- After Micro-Vertex Detector (MVD) installation in 2001 the ZEUS tracking package (VCTRAK) needed to be updated to benefit from the new detector
- A “fast” algorithm was needed for the use in the Third Level Trigger (TLT)
- VCMVD (VCtrak+MVD) has been developed to refine VCTRAK tracks by means of MVD hits
- Effects: great improvement in $a_4$, $a_3$ precision.
The ZEUS MVD

Barrel Section

- 3 layers of silicon detectors;
  - each layer measures 2 views: $r\phi$ and $z$;
- intrinsic resolution: $\sim 20 \mu m$;
- angular coverage (3 layers):
  $22^\circ < \theta < 159^\circ$.

Forward wheels

- 4 wheels of silicon detectors;
- extend coverage to $\theta = 7^\circ$.

Only BMVD is used in the package.
VCMVD: the method

- Tracks are found in CTD by VCTRAK;
- MVD hits are reconstructed;
- VCTRAK tracks are propagated from CTD to MVD;
- MVD hits are collected on the outer layer;
- track parameters are updated;
- the same procedure is repeated for middle and internal layers.
Results: efficiency

Geometrical coverage

- 2 layers: 72° in \( \phi \);
- 3 layers: 288° in \( \phi \);

Expected intersections:
\[ \langle n \rangle \approx 2.8/\text{track/view}. \]

Assigned clusters

- Single muon MC: \( \langle n \rangle = 2.9 \);
- \( b \bar{b} \) MC: \( \langle n \rangle = 2.4 \div 2.5 \);
- Data (offline): \( \langle n \rangle = 2.0 \).
Results: $D_H$ and $Z_H$

**Sample:** Single muon Monte Carlo, $p_T = 0.5 \div 1.5$ GeV

**Results**

- $\sigma(D_H)$: 650 $\mu$m (VCTRACK) $\rightarrow$ 300 $\mu$m (VCMVD);
- $\sigma(Z_H)$: 3.2 mm (VCTRACK) $\rightarrow$ 0.26 mm (VCMVD).

$\sigma(a_3)$

$\sigma(a_4)$

$\sigma(D_H)$ $\rightarrow$ 100 $\mu$m at high-$p_T$. 
Results: Execution Time

The execution time is evaluated as fraction of VCTRAK (CTD tracking package) time.

- **Monte Carlo**: 40% (single muon) → 11% ($b\bar{b}$).
- **Data (offline)**: $20 \div 25\%$.

Absolute execution time increases steeply for VCTRAK
**Results: $P_T$ and probabilities**

**SAMPLE:** Single muon Monte Carlo, $p_T = 0.5 \div 1.5$ GeV

### $P_T$ measurement

<table>
<thead>
<tr>
<th>ID</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1700</td>
<td>0.8236E-02</td>
<td>0.1336E-02</td>
</tr>
</tbody>
</table>

**Evts**

- **Before MVD Fit**
- **After MVD Fit**

### Probability of $a_i$:

#### Definition of probability:

$$P \left( \frac{(a_{\nu}^{fit} - a_{\nu}^{true})^2}{\sigma_{fit}^2}, 1 \right)$$

- **Flat probabilities:** fitting procedure is correct.
- **Peaks at 0:** hint of non gaussian tails.

### Additional Notes:

- $\sigma(P_T, \text{VCTR}AK) = 11$ MeV.
- $\sigma(P_T, \text{VCMVD}) = 8$ MeV.
Discussion

• A new vertex detector has been installed in 2001 at ZEUS
• The VCMVD tracking package has been developed to update VCTRAK parameters
• VCMVD package has been tested offline: very good results in execution time and tracking improvement
• VCMVD has been implemented in the online software: data are coming for further testing
Conclusions
Conclusions

Part I

• HERA collisions have been analysed in the search for multi-electron and di-muon events
• The data are nicely described by the SM simulation
• The excess observed by H1 in high-mass di/trielectrons is not confirmed

Part II

• A tracking package, VCMVD, has been developed for use of MVD in TLT
• VCMVD behaves well on (offline) data and MC
• Online data are coming for testing
ADDITIONAL SLIDES
The ZEUS detector
The Central Tracking Detector (CTD)

- Cylindrical wire drift chamber, 72 layers of sense wires divided into 9 super-layers.
- \(-100 \, \text{cm} < z < 104 \, \text{cm}, \, 15^\circ < \theta < 164^\circ\).
- Filled with Ar, CO\(_2\) and C\(_2\)H\(_6\) (ethane) in the proportion 85:5:1.
- Wires are tilted by 45\(^\circ\) to compensate the Lorentz angle.

The resolution on \(p_T\) for tracks with \(p_T > 150\) MeV, constrained to the interaction vertex and passing three CTD super-layers is

\[
\frac{\sigma(p_T)}{p_T} = 0.0058 \cdot \left(\frac{p_T}{\text{GeV}}\right) \oplus 0.0065 \oplus \frac{0.0014}{(p_T/\text{GeV})}.
\]

The CTD also supplies information on the energy loss \(dE/dx\).
The Uranium Calorimeter (CAL)

- Longitudinally divided into three parts (RCAL/BCAL/FCAL).
- Surrounds the tracking devices and the solenoid.
- Consists of 3.3 mm thick depleted uranium plates alternated with 2.6 mm thick organic scintillator.
- Compensation: same response for electrons and hadrons.

**Electromagnetic energy resolution**

\[
\frac{\sigma(E)}{E} = \frac{18\%}{\sqrt{E/\text{GeV}}} \oplus 2\%
\]

**Hadronic energy resolution**

\[
\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E/\text{GeV}}} \oplus 1\%
\]
The Barrel/Rear Muon Chambers

- Large area to be covered ⇒ modular structure based on the chamber.
- Two layers of LST tubes placed on both sides of a honeycomb support structure.
- \( x \) and \( y \) coordinates read by each LST plane (signal induced on conductive strips orthogonal to the wires, glued outside the plane).
- Cells filled with Ar, CO\(_2\) and C\(_4\)H\(_{10}\) (isobutane).
- Chambers have different shape and dimension, depending on their position.

\* BMUI-RMUI: chambers between the CAL and the yoke.
\* BMUO-RMUO: chambers outside the yoke.
The FMUON detector consists of:

- 4 LST trigger planes, with digital $\rho$ and $\phi$ read-out (LST1–4);
- Two coverage planes of LSTs, in the large polar angle region (LW1–2);
- 4 planes of drift chambers (DC1–4);
- Two large toroidal magnets, providing a 1.7 T field for momentum separation and measurement in the small polar angle region.

★ FMUI: LST1–DC1, inside the yoke.
★ FMUO: other chambers, outside the yoke.
The Lumi Monitor

- Photon calorimeter at 
  \[ z = -\left(104 \div 107\right) \text{ m}. \]

- Resolution:
  \[ \frac{\sigma(E)}{E} = \frac{23\%}{\sqrt{E/\text{GeV}}}. \]

- Photons from \( ep \rightarrow ep\gamma \) are counted.

- Luminosity is extracted using Bethe-Heitler formula for \( \sigma(ep \rightarrow ep\gamma) \).

- Precision: \( \sigma(L)/L = 1 \div 2\% \).
Past results
Data taking: 1994-00  \hspace{1cm} \textbf{Lumi used:} 115.2 \text{ pb}^{-1}

Event Selection

- Two "central" (20° < \( \theta < 150° \)), "isolated", electrons
- \( P_T \) cut: \( P_T^{e_1} > 10 \text{ GeV} \), \( P_T^{e_2} > 5 \text{ GeV} \)

Event Classification

- "2e": Only 2 central electrons
- "3e/4e": Additional "isolated" electrons (also Forward and Rear)
- \( \gamma\gamma \) subsample
  - Just 2 opposite charge electrons: \( ep \rightarrow e^+e^-X \)
  - \( E - P_z < 45 \text{ GeV} \) (ie \( y < 0.82 \), \( Q^2 < 1 \text{ GeV}^2 \))
  - "Cleaner" sample; scattered electron is lost in beam–pipe; both detected electrons come from interaction
Different topology for “2e” and “3e” events:

A “2e” event:

\[ P_T^{e1} = 63 \text{ GeV}, \quad P_T^{e2} = 62 \text{ GeV} \]
\[ M_{12} = 130 \text{ GeV} \]

\[ \rightarrow \text{Harder } P_T \text{ in “2e”} \]

A “3e” event:

\[ P_T^{e1} = 25 \text{ GeV}, \quad P_T^{e2} = 20 \text{ GeV} \]
\[ M_{12} = 118 \text{ GeV} \]

\[ \rightarrow \text{More forward } e^+e^- \text{ pairs in “3e”} \]
Multi-\(e\) at H1: global variables

H1 Preliminary

Multi-electron Analysis

- GRAPE: \(\gamma \gamma\) interaction + \(\gamma\) & \(Z^0\) conversion
- NC-DIS + Compton: fake "2e-3e" events

- Events vs. \(E-P_z\) (GeV)
  - H1 Data 115 pb\(^{-1}\)
  - GRAPE
  - NC-DIS + Compton

- Events vs. \(p_{\text{miss}}^T\) (GeV)
  - \(2e\)

- Events vs. \(p_{\text{hadrons}}^T\) (GeV)
  - \(3e\)
Multi-\(e\) at H1: electron variables

H1 Preliminary

Multi-electron Analysis

Three “2e” events with \(P_T^{e1} > 50 \text{ GeV}\) (but low SM expectation)
Multi-\(e\) at H1: Mass distributions

H1 Preliminary

\[ M_{12} = \text{Mass of two highest } P_T \text{ electrons} \]

\[ \text{Harder } P_T \text{ for “2e”} \]

At \( M_{12} > 100 \text{ GeV} \)

“2e” events:
3 found
0.25\( \pm \)0.05 expected

“3e” events:
3 found
0.23\( \pm \)0.04 expected
Multi-$\epsilon$ at H1: $\gamma\gamma$ Cross Section

- Extracted from “$\gamma\gamma$” sample
- Good Agreement with SM

$e^+e^-\rightarrow e^+ e^- X$

$P_{T}^{e_{1}} \geq 10 \text{ GeV}, P_{T}^{e_{2}} \geq 5 \text{ GeV}$

$20^{\circ} \leq \theta_{e_{1},e_{2}} \leq 150^{\circ}$

$y \leq 0.82, Q^{2} \leq 1 \text{ GeV}^{2}$

- $d\sigma/dP_{T}^{e_{1}} (\text{pb/GeV})$
- $d\sigma/dP_{T}^{\text{hadrons}} (\text{pb/GeV})$
- $d\sigma/dM_{12} (\text{pb/GeV})$

H1 Data
SM (GRAPE)
### Multi-electrons at H1: Overview

<table>
<thead>
<tr>
<th>Selection</th>
<th>DATA</th>
<th>SM</th>
<th>GRAPE</th>
<th>NC-DIS + Compton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible 2e</td>
<td>105</td>
<td>118.2±12.8 *</td>
<td>93.3±11.5</td>
<td>25.0±5.5</td>
</tr>
<tr>
<td>Visible 3e</td>
<td>16</td>
<td>21.6±3.0</td>
<td>21.5±3.0</td>
<td>0.1±0.1</td>
</tr>
<tr>
<td>Visible 4e or more</td>
<td>0</td>
<td>0.1±0.0</td>
<td>0.1±0.0</td>
<td>0.0±0.0</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow e^+e^-$ subsample</td>
<td>41</td>
<td>48.3±6.1</td>
<td>46.4±6.1</td>
<td>1.9±0.9</td>
</tr>
<tr>
<td>Visible 2e $M(12) &gt; 100$</td>
<td>3</td>
<td>0.25±0.05</td>
<td>0.21±0.04</td>
<td>0.04±0.03</td>
</tr>
<tr>
<td>Visible 3e $M(12) &gt; 100$</td>
<td>3</td>
<td>0.23±0.04</td>
<td>0.23±0.04</td>
<td>0.00±0.00</td>
</tr>
</tbody>
</table>

* Statistical ⊕ Systematic Uncertainty

- DATA agree with SM at low $M_{12}$
- Excess in DATA at high $M_{12}$
Multi-electrons at ZEUS

Data taking: 1994-00  
Lumi used: 130.5 pb$^{-1}$

Event Selection

- “Good Vertex”: $|Z_{vtx}| < 50$ cm
- Two “central” ($17^\circ < \theta < 164^\circ$) electrons: $E_{e1}^T > 10$ GeV, $E_{e2} > 10$ GeV

A “2e” event
Multi-$\epsilon$ at ZEUS: electron variables

![Graphs showing electron variables](multielectron.png)

Good Agreement
Multi-$e$ at ZEUS: Mass distribution

Two events with $M_{12} > 100$ GeV; expected $1.2 \pm 0.1$
### Multi-\(e\) at ZEUS: Overview

<table>
<thead>
<tr>
<th>Type</th>
<th>Data</th>
<th>SM</th>
<th>GRAPE</th>
<th>NC-DIS</th>
<th>Compton</th>
</tr>
</thead>
<tbody>
<tr>
<td>2e</td>
<td>191</td>
<td>213.9±3.9 *</td>
<td>182.2±1.2</td>
<td>23.9±3.7</td>
<td>7.8±0.5</td>
</tr>
<tr>
<td>(E_T^{e1} &gt; 30) GeV</td>
<td>6</td>
<td>5.7±0.3</td>
<td>4.4±0.2</td>
<td>0.9±0.2</td>
<td>0.4±0.1</td>
</tr>
<tr>
<td>(M_{12} &gt; 100) GeV</td>
<td>2</td>
<td>0.77±0.08</td>
<td>0.47±0.05</td>
<td>0.12±0.06</td>
<td>0.18±0.03</td>
</tr>
</tbody>
</table>

#### 3e sample

| 3e | 26 | 34.7±0.5 | 34.7±0.5 | - | - |
| \(E_T^{e1} > 30\) GeV | 2 | 1.43±0.08 | 1.43±0.08 | - | - |
| \(M_{12} > 100\) GeV | 0 | 0.37±0.04 | 0.37±0.04 | - | - |

* Only Statistical Error
Di-Muons at H1

Data taking: 1999-00
Lumi used: 70.9 pb$^{-1}$

Muon Selection

- Reconstructed track in both CTD and Muon Detectors
- Angular region: $20^\circ < \theta < 160^\circ$
- For low momentum muons: CTD Track + Calorimeter MIP

Event Selection

- Two muons: $P_{T}^{\mu_1} > 2.00$ GeV, $P_{T}^{\mu_2} > 1.75$ GeV
- Invariant mass cut: $M_{\mu\mu} > 5$ GeV
- Muon Isolation: $D_{Trk, jet}^{\mu} > 1.0$ in $\eta\phi$ (or $D_{Trk, jet}^{\mu} > 0.5$ if $P_{T}^{\mu} > 10$ GeV)
Di-Muons at H1: Cross section

**Main contribution:** $\gamma \gamma$ interaction

**Small contribution to $\mu^+\mu^-$ from:**
- $\Upsilon$, $\bar{q}q$ and $\tau\tau$ decays

**Total Cross-Section:** $\sigma = 46.5 \pm 1.3 \pm 4.7$ pb

**Good Agreement with SM:** $\sigma(\text{GRAPE}) = 46.2$ pb
Di-Muons at H1: Cross section

H1 Muon Pair Analysis (ep → epμμ)

Elastic

Inelastic

Inelastic Cross–Section: $\sigma^{\text{inel}} = 20.8\pm0.9\pm3.3$ pb

Good Agreement with SM: $\sigma^{\text{inel}}(\text{GRAPE}) = 21.5$ pb

- Elastic and Inelastic separated by tagging proton remnant
Di-Muons at ZEUS

Data taking: 1997-00
Lumi used: 105.2 pb$^{-1}$

Muon Selection

- Track in CTD ($P_T > 5$ GeV)+ MIP in CAL
- Angular region: $20^\circ < \theta < 160^\circ$

Event Selection

- Two muons: $1\mu$ matched to muon chambers
- Muon Isolation: $N_{\text{trks}}(R_{\eta \phi} < 1) = 0$
- Good Vertex: $|Z_{vtx}| < 40$ cm, $\sqrt{X_{vtx}^2 + Y_{vtx}^2} < 0.5$ cm
- Acollinearity: $\cos(\Omega) > -0.995$
Multi-electron search
The electron tagging

The EM electron finder analyses energy deposits in the CAL to distinguish electromagnetic from hadronic clusters.

Sketch of the algorithm:

- Calorimeter cells are grouped in clusters;
- 4 quantities are evaluated for each cluster:
  - fraction of hadronic energy,
  - fraction of electromagnetic energy outside two highest-energy modules,
  - fraction of energy outside two highest-energy modules,
  - non-electron energy in a R=0.8 cone in $\eta\phi$;
- when a CTD track matches the cluster, are evaluated:
  - $\theta_{Trk} - \theta_{Cal}$,
  - $\phi_{Trk} - \phi_{Cal}$,
  - $1/P_{Trk} - 1/E_{Cal}$;
- a probability is computed using the above defined quantities.
Variable reconstruction

Very nice correlation of true and reconstructed variables:
Variable reconstruction

Resolutions:

- $\sigma(\theta)/\theta = 0.5\%$;
- $\sigma(P_T)/P_T = 10\%$;
- $\sigma(\cos \Omega)/\cos \Omega = 2\%$;
- $\sigma(M_{12})/M_{12} = 10\%$.

- Excellent resolution for angles.
- Good resolution for energies.
Trigger chain

Di-electron chain

- Elastic di-\(e\): good vertex + few CTD tracks + 2 electrons.
- Inelastic di-\(e\): good vertex + 2 electrons + high mass.

Neutral Current DIS chain

- good vertex + 1 electron + large \(E_T\) + large \(Q^2\) + large \(E - P_z\).

High-\(E_T\) chain

- high \(E_T\) in the CAL.
## Data to MC comparison: $2e$

1996-2000 data taking → $L=120.49$ pb$^{-1}$

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>All SM</th>
<th>di-ele MC</th>
<th>NC-DIS MC</th>
<th>QED-C MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>All $2e$</td>
<td>183</td>
<td>197.78</td>
<td>169.11</td>
<td>18.57</td>
<td>10.10</td>
</tr>
<tr>
<td>$M_{12} &gt; 50$ GeV</td>
<td>17</td>
<td>27.47</td>
<td>22.68</td>
<td>3.32</td>
<td>1.47</td>
</tr>
<tr>
<td>$M_{12} &gt; 100$ GeV</td>
<td>1</td>
<td>0.67</td>
<td>0.46</td>
<td>0.08</td>
<td>0.13</td>
</tr>
</tbody>
</table>

### Graphical Content

#### ZEUS $2e$

- **Variables:**
  - $E_T^{e1}, E_T^{e2}$ (GeV)
  - $\theta^{e1}, \theta^{e2}$ (rad)
  - $M_{12}$ (GeV)
  - $\phi^{e1}, \phi^{e2}$ (rad)
  - $|\theta^{e1} - \theta^{e2}|$ (rad)
  - $(E-P^z)_{ee}$ (GeV)

- **Data Points:**
  - ZEUS 1996-00
  - GRAPE+NC+QEDC
  - NC+QEDC
  - QEDC

- **Graphs:**
  - Plots showing distributions for each variable.

---

Multi-leptons at HERA – MVD tracking at ZEUS TL T – p.65/92
Data to MC comparison: $2e$


Multi-leptons at HERA – MVD tracking at ZEUS TL T – p.66/92
Data to MC comparison: 3e

1996-2000 data taking → L=120.49 pb⁻¹

<table>
<thead>
<tr>
<th>Selection</th>
<th>Data</th>
<th>All SM</th>
<th>di-ele MC</th>
<th>NC-DIS MC</th>
<th>QED-C MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 3e</td>
<td>26</td>
<td>38.03</td>
<td>37.88</td>
<td>0.15</td>
<td>0.00</td>
</tr>
<tr>
<td>$M_{12} &gt; 50$ GeV</td>
<td>6</td>
<td>7.54</td>
<td>7.46</td>
<td>0.08</td>
<td>0.00</td>
</tr>
<tr>
<td>$M_{12} &gt; 100$ GeV</td>
<td>0</td>
<td>0.44</td>
<td>0.44</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

ZEUS 3e

Multi-leptons at HERA – MVD tracking at ZEUS TL T – p.67/92
Data to MC comparison: 3e


Multi-leptons at HERA – MVD tracking at ZEUS TLT – p.68/92
Cross section: Method

- \( N_g \): MC events generated;
- \( N^r \): MC events reconstructed;
- \( N^r_g \): MC events generated AND reconstructed;
- \( N_d \): events selected in data.

Definitions

- efficiency: \( e = \frac{N^r_g}{N_g} \);
- purity: \( p = \frac{N^r_g}{N^r} \);
- acceptance: \( a = \frac{N^r}{N^r_g} \).

Cross section

Total:

\[
\sigma_{MC} = \frac{N_g}{L}
\]

\[
\sigma_{DATA} = \frac{N_d}{L a}
\]

Differential:

\[
\frac{d\sigma_{MC}}{dx} = \frac{N_g}{L \Delta x}
\]

\[
\frac{d\sigma_{DATA}}{dx} = \frac{N_d}{L a \Delta x}
\]
Correction for $\sqrt{s}$

To refer cross-section to $\sqrt{s} = 318$ GeV:

$$\sigma_{x}^{318} = \frac{\sigma_{MC}^{99-00}}{\sigma_{x}^{MC}} \sigma_{x}^{DATA}$$

$x = 1996-97$ or $1998-99$

Combination of periods

$$\sigma_{96-00} = \frac{\sum_{x} \sigma_{x}^{318} L_{x}}{\sum_{x} L_{x}}$$

## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Type</th>
<th>Variation</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi measurement</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>CAL energy scale</td>
<td>5%</td>
<td>+9.4%</td>
</tr>
<tr>
<td>Prob. cut in EM</td>
<td>$P_{\text{grand}} &gt; 0.01 \rightarrow 0.1$</td>
<td>-4.1%</td>
</tr>
<tr>
<td></td>
<td>$P_{\text{cal}} &gt; 0.1 \rightarrow 0.2$</td>
<td>-4.8%</td>
</tr>
<tr>
<td>Isolation cut</td>
<td>$E_{\text{cone}} &lt; 0.3 \rightarrow 0.2$ GeV</td>
<td>+7.3%</td>
</tr>
<tr>
<td>Mass cut</td>
<td>8%</td>
<td>0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>+13%</td>
</tr>
</tbody>
</table>

→ **Statistical uncertainty:** $\pm 14\%$. 

---

**UCAL Energy Scale**

**Probability cut in EM**

**Isolation cut**

[Graphs showing variations in UCAL Energy Scale, Probability cut in EM, and Isolation cut]
### Cross section: Tables

<table>
<thead>
<tr>
<th>Bin definition</th>
<th>Pur.</th>
<th>Acc.</th>
<th>$\frac{d\sigma_{\text{DATA}}}{dx}$ (pb/[x])</th>
<th>$\frac{d\sigma_{\text{MC}}}{dx}$ (pb/[x])</th>
</tr>
</thead>
<tbody>
<tr>
<td>$15 &lt; M_{12} &lt; 25$ GeV</td>
<td>0.723</td>
<td>0.309</td>
<td>$(4.2 \pm 1.1 \pm 1.0)E^{-02}$</td>
<td>$5.7E^{-02}$</td>
</tr>
<tr>
<td>$25 &lt; M_{12} &lt; 40$ GeV</td>
<td>0.840</td>
<td>0.330</td>
<td>$(5.2 \pm 1.0 \pm 0.6)E^{-02}$</td>
<td>$4.5E^{-02}$</td>
</tr>
<tr>
<td>$40 &lt; M_{12} &lt; 60$ GeV</td>
<td>0.803</td>
<td>0.206</td>
<td>$(1.50 \pm 0.57^{+0.34}_{-0.32})E^{-02}$</td>
<td>$1.38E^{-02}$</td>
</tr>
<tr>
<td>$10 &lt; P_T^{e} &lt; 15$ GeV</td>
<td>1.154</td>
<td>0.223</td>
<td>$(2.20 \pm 0.42^{+0.28}_{-0.20})E^{-01}$</td>
<td>$1.94E^{-01}$</td>
</tr>
<tr>
<td>$15 &lt; P_T^{e} &lt; 20$ GeV</td>
<td>1.073</td>
<td>0.236</td>
<td>$(5.6 \pm 2.1^{+1.1}_{-1.0})E^{-02}$</td>
<td>$4.9E^{-02}$</td>
</tr>
<tr>
<td>$20 &lt; P_T^{e} &lt; 25$ GeV</td>
<td>0.924</td>
<td>0.239</td>
<td>$(1.13 \pm 0.93^{+0.45}_{-0.43})E^{-02}$</td>
<td>$1.69E^{-02}$</td>
</tr>
<tr>
<td>$0.349 &lt; \theta_{e} &lt; 1.105$ rad</td>
<td>0.831</td>
<td>0.381</td>
<td>$(6.6 \pm 1.4^{+1.0}_{-0.9})E^{-01}$</td>
<td>$7.2E^{-01}$</td>
</tr>
<tr>
<td>$1.105 &lt; \theta_{e} &lt; 1.862$ rad</td>
<td>0.828</td>
<td>0.334</td>
<td>$(5.1 \pm 1.4 \pm 0.6)E^{-01}$</td>
<td>$5.6E^{-01}$</td>
</tr>
<tr>
<td>$1.862 &lt; \theta_{e} &lt; 2.618$ rad</td>
<td>0.681</td>
<td>0.198</td>
<td>$(8.1 \pm 2.2^{+1.2}_{-1.0})E^{-01}$</td>
<td>$6.8E^{-01}$</td>
</tr>
</tbody>
</table>
Di-muon search
Muon tagging: GLOMU

The GLOMU package tags muons in the barrel/rear region. It combines info from inner B/RMUON, CTD, CAL.

Sketch of the algorithm:

- CTD tracks with high momentum and close to vertex are collected;
- B/RMUON tracks are collected;
- MIP-like deposits are searched in the CAL;
- a match is attempted in $\theta$-$\phi$ for these objects;
- a cut $\chi^2 < 20$ is set to accept a match.
Muon tagging: MPMATCH2 and MIPs

The MPMATCH2 package tags muons in the forward region. It combines info from inner FMUON and CTD.

Sketch of the algorithm:

• tracks are reconstructed in the FMU detector;
• these tracks are backwards propagated to the CAL surface;
• CTD tracks are extrapolated to the same surface;
• a match is attempted of the two sets of tracks;
• track parameters are refitted.

To raise efficiency in muon finding, a matching of CTD tracks and MIP-like deposits in the CAL is attempted.

• CTD tracks are extrapolated to the CAL and matched to MIP-like deposits.
Variable reconstruction

Very nice correlation of true and reconstructed variables:
Variable reconstruction

Resolutions:

- $\sigma(\theta)/\theta = 0.3\%$;
- $\sigma(P_T)/P_T = 10 \div 15\%$;
- $\sigma(\cos \Omega)/\cos \Omega = 1\%$;
- $\sigma(M_{\mu\mu})/M_{\mu\mu} = 10\%$.

→ Excellent resolution for angles.
→ Good resolution for energies.
Trigger chain

B/RMUON chain

- Inner chambers trigger: (few CTD tracks + B/RMUI signal) OR (B/RMUI signal matched to CTD tracks and MIP-like deposits).
- Outer chambers trigger: Signal in B/RMUI and B/RMUO + CAL activity and CTD tracks
- Both chains: a GLOMU matching

FMUON chain

- few CTD tracks + matching (FMU and MIP-like deposits) + two CTD tracks with high invariant mass
B/RMUI Efficiencies

B/RMU inefficiencies are not simulated in MC

Efficiencies were measured (M. Turcato, A. Bertolin, M. Corradi)

Method

Di-muon events are selected ($J/\psi$, Bethe-Heitler, ...) by

- A hit in muon chambers
- 2 CTD tracks with $M > 2.5$ GeV
- Acollinearity: $\cos \Omega > -0.95$

The efficiency is

$$e = \frac{\text{No. of GLOMU tracks}}{\text{No. of CTD tracks}}$$

Results

The ratio $R = \frac{e(\text{DATA})}{e(\text{MC})}$ is used to weight Monte Carlo samples

<table>
<thead>
<tr>
<th>Region</th>
<th>Data/MC ratio Years 1996-97</th>
<th>Data/MC ratio Years 1998-2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMUI</td>
<td>0.854 ± 0.061</td>
<td>0.709 ± 0.042</td>
</tr>
<tr>
<td>RMUI</td>
<td>0.819 ± 0.068</td>
<td>0.853 ± 0.050</td>
</tr>
</tbody>
</table>

BMUI cut: $4.25 < P_T^\mu < 10$ GeV

RMUI cut: $5 < P_T^\mu < 10$ GeV
Di-muon events

→ Three events found around $M_{\mu\mu} = 50$ GeV
→ All of them look like genuine di-muons
### Systematic uncertainties

<table>
<thead>
<tr>
<th>Type</th>
<th>Variation</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi measurement</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>B/RMUI Efficiency</td>
<td>7.5% in 1996–97, 6.0% in 1998–00</td>
<td>+5.4%, −4.8%</td>
</tr>
<tr>
<td>cos Ω cut</td>
<td>cos Ω &gt; −0.995 → −0.985</td>
<td>+2.8%</td>
</tr>
<tr>
<td>Isolation cut</td>
<td>$D^{\mu}_{\text{Trk}} &gt; 1 \rightarrow 2$</td>
<td>+4.0%</td>
</tr>
<tr>
<td>Prob. cut</td>
<td>$\chi^2 &lt; 20 \rightarrow 10$ (GLOMU), $P &gt; 0.01 \rightarrow 0.05$ (MPMATCH2)</td>
<td>−0.4%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>+7.2%, −6.6%</td>
</tr>
</tbody>
</table>

Statistical uncertainty: ±6.9%.
## Cross section: Tables

<table>
<thead>
<tr>
<th>Bin definition</th>
<th>Pur.</th>
<th>Acc.</th>
<th>$\frac{d\sigma_{\text{DATA}}}{dx}$ (pb/[x])</th>
<th>$\frac{d\sigma_{\text{MC}}}{dx}$ (pb/[x])</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10 &lt; M_{\mu\mu} &lt; 20$ GeV</td>
<td>0.968</td>
<td>0.437</td>
<td>$(3.44 \pm 0.28)_{-0.22}^{+0.24} E^{-01}$</td>
<td>$3.70 E^{-01}$</td>
</tr>
<tr>
<td>$20 &lt; M_{\mu\mu} &lt; 30$ GeV</td>
<td>0.977</td>
<td>0.412</td>
<td>$(8.0 \pm 1.4)_{-0.7}^{+0.8} E^{-02}$</td>
<td>$10.7 E^{-02}$</td>
</tr>
<tr>
<td>$30 &lt; M_{\mu\mu} &lt; 45$ GeV</td>
<td>0.928</td>
<td>0.388</td>
<td>$(2.02 \pm 0.58)_{-0.31}^{+0.32} E^{-02}$</td>
<td>$2.40 E^{-02}$</td>
</tr>
<tr>
<td>$45 &lt; M_{\mu\mu} &lt; 100$ GeV</td>
<td>0.787</td>
<td>0.437</td>
<td>$(2.04 \pm 0.91)_{-0.65}^{+0.91} E^{-03}$</td>
<td>$1.90 E^{-03}$</td>
</tr>
<tr>
<td>$5 &lt; P_T^{\mu} &lt; 6.5$ GeV</td>
<td>0.949</td>
<td>0.401</td>
<td>$(1.53 \pm 0.16)_{-0.10}^{+0.11}$</td>
<td>$1.55$</td>
</tr>
<tr>
<td>$6.5 &lt; P_T^{\mu} &lt; 8$ GeV</td>
<td>1.009</td>
<td>0.437</td>
<td>$(7.6 \pm 1.1)_{-0.5}^{+0.6} E^{-01}$</td>
<td>$8.3 E^{-01}$</td>
</tr>
<tr>
<td>$8 &lt; P_T^{\mu} &lt; 13$ GeV</td>
<td>0.994</td>
<td>0.447</td>
<td>$(2.17 \pm 0.31)_{-0.22}^{+0.23} E^{-01}$</td>
<td>$2.72 E^{-01}$</td>
</tr>
<tr>
<td>$13 &lt; P_T^{\mu} &lt; 50$ GeV</td>
<td>0.885</td>
<td>0.473</td>
<td>$(7.9 \pm 2.1)_{-1.2}^{+1.3} E^{-03}$</td>
<td>$10.3 E^{-03}$</td>
</tr>
<tr>
<td>$0.262 &lt; \theta_{\mu} &lt; 0.912$ rad</td>
<td>0.963</td>
<td>0.339</td>
<td>$2.36 \pm 0.42_{-0.17}^{+0.18}$</td>
<td>$2.81$</td>
</tr>
<tr>
<td>$0.912 &lt; \theta_{\mu} &lt; 1.562$ rad</td>
<td>0.977</td>
<td>0.523</td>
<td>$1.65 \pm 0.22_{-0.12}^{+0.13}$</td>
<td>$1.83$</td>
</tr>
<tr>
<td>$1.562 &lt; \theta_{\mu} &lt; 2.212$ rad</td>
<td>0.970</td>
<td>0.516</td>
<td>$1.83 \pm 0.23_{-0.13}^{+0.14}$</td>
<td>$1.69$</td>
</tr>
<tr>
<td>$2.212 &lt; \theta_{\mu} &lt; 2.862$ rad</td>
<td>0.963</td>
<td>0.385</td>
<td>$1.41 \pm 0.24_{-0.13}^{+0.14}$</td>
<td>$1.84$</td>
</tr>
</tbody>
</table>
MVD tracking at ZEUS TLT
**Track parameterisation**

**Coordinates**

\[
x(\phi) = x_0 + \left( a_3 + \frac{1}{a_2} \right) \sin a_1 - \frac{\sin \phi}{a_2}
\]

\[
y(\phi) = y_0 - \left( a_3 + \frac{1}{a_2} \right) \cos a_1 + \frac{\cos \phi}{a_2}
\]

\[
z(\phi) = a_4 - \frac{a_5}{a_2} (\phi - a_1)
\]

**PathLength**

\[
s = - \frac{\phi - a_1}{a_2}
\]
The ZEUS MVD: design

Sensor design

- 64x64 mm $n$-type silicon sensors
- $p^+$ strips every 20 $\mu$m
- a strip over 6 is read-out

BMVD design

- Two sensors form a “half-module”
- Two half-modules form a “module”, 2.2% $X_0$ thick
- A module measures $r\phi$ and $z$ coordinates
The ZEUS MVD: performances

Test beam

Cluster resolution on a single detector (6 GeV beam), with different reconstruction algorithms.

Example: $c$-quark selection

$\rightarrow$ Using $D^*$ tagging:

\[ \text{eff} \approx 1\% \text{ @ pur} \approx 30\% \]

$\rightarrow$ Using MVD (simulation):

\[ \text{eff} \approx 10\text{–}20\% \text{ @ pur} \approx 30\% \]
The clustering procedure

Procedure

• Pedestal and common mode are subtracted;
• Consecutive strips above threshold are clustered;
• Centre and width: accordingly to centre of gravity:

\[
\langle \xi \rangle = \frac{1}{Q} \sum_i Q_i \xi_i
\]

\[
\sigma^2(\xi) = \frac{1}{Q} \sum_i Q_i (\xi_i - \langle \xi \rangle)^2
\]

Results

<table>
<thead>
<tr>
<th>ID</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000000</td>
<td>2000</td>
<td>1.061</td>
<td>0.1247</td>
</tr>
<tr>
<td>3201</td>
<td>12781</td>
<td>0.8390E-02</td>
<td>0.1683E-02</td>
</tr>
</tbody>
</table>

2003/10/25 16:31

→ Left: Eff = (No. of meas. hits)/(No. of GEANT hits)
→ Right: Cluster widths
→ Results obtained on a single \( \mu \) MC
Multiple scattering

Scattering angle

$$\delta_{2D} = \frac{0.0136}{p/\text{GeV}} \sqrt{D} \left(1 + 0.0038 \ln D\right)$$

$$\delta_{\text{RMS}} = \frac{\delta_{2D}}{|\sin \theta|}$$

Effect on covariance matrix

$$\text{cov}(a_1, a_1) \rightarrow \text{cov}(a_1, a_1) + \delta_{\text{RMS}}^2$$

$$\text{cov}(a_1, a_3) \rightarrow \text{cov}(a_1, a_3) + Q s \delta_{\text{RMS}}^2$$

$$\text{cov}(a_3, a_3) \rightarrow \text{cov}(a_1, a_3) + \left(s \delta_{\text{RMS}}\right)^2$$

Minor effect on the other covariances

Dead materials:

- Ladders (rectangular boxes);
- Support tube (cylinder);
- Beam pipe (ellipsoidal cylinder).

$D$ is the traversed material (g/cm$^2$)
Energy loss

Bethe-Bloch Formula:

\[-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right]\]

where:

- $K = 3.07075 \cdot 10^{-4}$ GeV cm$^2$ mol$^{-1}$
- Incident particle:
  - $z$ is the charge number
  - $M$ is the mass
  - $\beta c$ is the particle speed
  - $\gamma = 1/\sqrt{1 - \beta}$
  - $T_{\text{max}} = \frac{2m_e c^2 \beta^2 \gamma^2}{1+2\gamma m_e/M}$
- Medium:
  - $Z/A$: atomic / mass number
  - $I$ is the mean excitation energy
  - $\delta$ is the density effect correction

Multi-leptons at HERA – MVD tracking at ZEUS TLT – p.89/92
Each helix is propagated inwards;
intersections with ladders are found;
the closest BMVD hit is collected;
track parameters are updated;
the procedure is iterated for the remaining layers;
external layer only: hits are preferred which leads to hits in the internal layers.
Multiple assignment

→ The same hit may be assigned to more tracks.
→ If one hit is present:
  • hit is assigned to the closest track
→ If two or more hits are present:
  • assignment is done to minimise
    \[
    \frac{(\text{Trk}_1 - \text{Clu}_n)^2}{\sigma^2} + \frac{(\text{Trk}_2 - \text{Clu}_m)^2}{\sigma^2}
    \]
Parameter Fit

Measurement

- $F_m \pm \sigma_m$: measurement No. $m$
- $f(m; \vec{a})$: expected position

Before fit

$\chi^2_0$ of old fit (minimised wrt $\vec{a}$).

A measurement $F_m$ is added.

$\chi^2(\vec{a}) = \chi^2_0 + \frac{[F_m - f(m; \vec{a})]^2}{\sigma_m^2}$

$B_\mu(\vec{a}) = -\frac{1}{2} \frac{\partial \chi^2(\vec{a})}{\partial a_\mu}$

$U_{\mu\nu}(\vec{a}) = -\frac{B_\mu(\vec{a})}{\partial a_\mu}$

$\chi^2(\vec{a})$ is no more minimised.

$\chi^2$ Minimisation

Parameter $\vec{a}$ is updated by minimising $\chi^2$: $\frac{\partial \chi^2(\vec{a} + \delta \vec{a})}{\partial a_\mu} = 0$

$\delta a_\mu = U^{-1}_{\mu\nu}(\vec{a}) B_\nu(\vec{a})$

After fit

- $\vec{a}_{\text{new}} = \vec{a} + \delta \vec{a}$;
- $B_\mu(\vec{a}_{\text{new}}) = 0$;
- $U_{\mu\nu}(\vec{a}_{\text{new}}) = U_{\mu\nu}(\vec{a})$;
- $\chi^2(\vec{a}_{\text{new}}) = \chi^2(\vec{a}) - B_\mu(\vec{a}) \delta a_\mu$. 