Electroweak Physics
in ep Collisions at HERA

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on behalf of the

Collaborations
Electroweak Physics at HERA

- **NC** and **CC** cross section (unpolarised)
- W mass and electroweak parameters
- **CC** cross section with polarised leptons (HERA II)
- Isolated Leptons and missing pT (HERA II)
- W Production

➡ What is new compared to summer (ICHEP)
HERA: ep Collider and Experiments

\[ E_e = 27.6 \text{ GeV} \]
\[ E_p = 920 \text{ GeV} \]

[Diagram of the HERA accelerator complex with labels for different energies and experiments.]
HERA Delivered Luminosities

longitudinally polarised electron beam

longitudinally polarised positron beam

2005:
H1 40 pb⁻¹
ZEUS 60 pb⁻¹

2004:
H1 and ZEUS 50 pb⁻¹

1992-2000:
H1 and ZEUS ~130 pb⁻¹
DIS – Neutral Current (NC)

deep inelastic scattering (DIS):

\[ Q^2 = - (k - k')^2 \]

\[ p_q = xP \]

\[ Q^2: \text{ four-momentum transfer} \]

\[ \text{spatial resolution } \sim \frac{1}{Q} \]

\[ \Rightarrow 10^{-16} \text{ cm} \]

\[ x: \text{ fractional momentum of the struck quark} \]

H1 detector
DIS - Charged Current (CC)

deep inelastic (DIS) scattering:

\[ Q^2 = - (k-k')^2 \]

H1 detector

\[ p_T^{\text{miss}} = 106 \text{ GeV} \]
Deep Inelastic Scattering at High $Q^2$

(unpolarized beams)

\[ \sim \frac{1}{Q^4} \]

photons

\[ \sim \left[ \frac{M_W^2}{Q^2 + M_W^2} \right]^2 \]

W boson

Unification of electromagnetic and weak interactions
Determination of W-Mass

\[
\frac{d^2\sigma_{cc}^{\pm}}{dx \, dQ^2} = \frac{G^2}{2\pi} \cdot \left(\frac{M_w^2}{Q^2 + M_w^2}\right)^2 \cdot \Phi^\pm(pdfs)
\]

Mw is propagator mass (enters in Q2 dependency)

Fermi constant G includes most of the radiative corrections

\[
\frac{d^2\sigma_{cc}^{\pm}}{dx \, dQ^2} = \frac{\pi\alpha^2}{4M_w^4} \cdot \left(1 - \frac{M_w^2}{M_Z^2}\right)^2 \cdot \frac{1}{1 - \Delta r} \cdot \left(\frac{M_w^2}{Q^2 + M_w^2}\right)^2 \cdot \Phi^\pm(pdfs)
\]

OMS scheme: Mw also enters in normalization

Radiative correction Δr computed in SM framework

- model independent measurement
- t-channel exchange unique at HERA
- Standard Model-dependent (H. Spiesberger: EPRC)

On Mass Shell renormalisation scheme

- combined EW-QCD fit to determine EW parameters accounting for their correlation with parton distributions
Results of Mass Fits:

**G-Propagator**

\[ M_W = 82.87 \pm 1.83 \, \text{(exp)} \pm 0.30 \, \text{(mod)} \, \text{GeV} \]

Model uncertainties \((\alpha_s, Q^2, \ldots)\)

**OMS Scheme**

\[ M_W = 80.786 \pm 0.207 \, \text{(exp)}^{+0.048}_{-0.029} \, \text{(mod)} \pm 0.025 \, \text{(top)} \pm 0.033 \, \text{(th)} - 0.084 \, \text{(Higgs)} \, \text{GeV} \]

\[ (120 \rightarrow 300 \, \text{GeV}) \]

\[ \sin^2 \theta_W = 0.2151 \pm 0.0040 \, \text{(exp)}^{+0.0019}_{-0.0011} \, \text{(th)} \]

→ consistent with the Standard Model
Quark Couplings to the Z Boson

\[ F_2 = \sum_q \left[ e_q^2 - 2e_q v_e v_e \chi_Z + \left( v_q^2 + a_q^2 \right) v_e^2 + a_e^2 \chi_Z^2 \right] x(q + \bar{q}) \]

\[ xF_3 = \sum_q \left[ -2e_q a_q a_e \chi_Z + 4v_q a_q v_e a_e \chi_Z^2 \right] x(q - \bar{q}) \]

\[ a_q = I_3^L \quad \text{Axial coupling, } I^3=+1/2 \text{ for } u, -1/2 \text{ for } d \]

\[ v_q = I_3^L - 2e_q \sin^2 \theta_W \quad \text{Vector coupling} \]

→ already as sensitive as LEP
→ polarisation: shrinks in $v_u$
→ removes LEP ambiguities

Fit: PDF+couplings

H1 preliminary

- $v_u$-PDF
- $v_d$-PDF

$68\% \text{ CL}$

Standard Model

LEP EWWG preliminary (Feb. 05)
CC with Polarized Leptons

ZEUS $e^+p$, 31 pb$^{-1}$, $P_e = +32\%$, -40\%  
New: H1 $e^-p$, 18 pb$^{-1}$, $P_e = -25\%$

$\Rightarrow$ good understanding of detectors
CC with Polarised Leptons

$$\sigma^\pm_{CC} = (1 \pm P) \sigma^{(P=0)}_{CC}$$

$$P = (N_{RH} - N_{LH}) / (N_{RH} + N_{LH})$$

**NEW:**

- first measurements of the helicity dependence of the CC cross section
- no hint for right-handed CC

$$\sigma_{e^+ p \rightarrow \bar{\nu} X} (P_{e^+} = -1) = 0.2 \pm 1.8 \text{(stat)} \pm 1.6 \text{(sys)} \text{ pb}$$

**2004**

- $$e^+ p \rightarrow \bar{\nu} X$$
  - H1 (prel.)
  - H1
  - ZEUS (prel.)
  - ZEUS

**2005**

- $$e^- p \rightarrow \nu X$$
  - SM (MRST)

$$Q^2 > 400 \text{ GeV}^2$$

$$y < 0.9$$
High $p_T$ Lepton Events at HERA

$e^+p \rightarrow \mu^+ X + \text{PTmiss}$

- isolated lepton (e or $\mu$)
- high hadronic $p_T$
- missing calorimeter $p_T$

**Possible other explanations:**

Anomalous top production, **RPV SUSY**: e.g. $ep \rightarrow \bar{t} \rightarrow \bar{b}W$ (talk by C.N. Nguyen)

**Standard Model:**

dominated by $W$ production

**in NLO-QCD**: Diener, C.S., Spira

High $p_t$, Lepton Events at HERA

Example of Tau Candidate

$$P_T^{CAL} = 39 \text{ GeV} \quad P_T^X = 37 \text{ GeV} \quad M_T = 68 \text{ GeV}$$

$\tau$ jet: collimated "pencil like"
Isolated Leptons at HERA II

H1 Collaboration (updated since ICHEP)

HERA II: complete positron sample

HERA I+II combined electron+positron

Search for \(l+P_T^{\text{miss}}\) events at HERA II (53 pb\(^{-1}\))

- H1 Data (prelim.) \(N_{\text{Data}} = 10\)
- All SM \(N_{\text{SM}} = 6.1 \pm 0.9\)

\(\rightarrow\) slight excess at high \(p_T^X\)

Search for \(l+P_T^{\text{miss}}\) events at HERA 1994-2005 (\(e^+p\), 192 pb\(^{-1}\))

- H1 Data (prelim.) \(N_{\text{Data}} = 34\)
- All SM \(N_{\text{SM}} = 23.3 \pm 3.1\)

\(\rightarrow\) clear excess at high \(p_T^X\)
Updated Isolated Lepton Results at HERA II

**H1 1994-2005**

<table>
<thead>
<tr>
<th>$\mathcal{L}(e^{\pm}p) = 192 \text{ pb}^{-1}$</th>
<th>Electron obs./exp.</th>
<th>Muon obs./exp.</th>
<th>Tau$^{\text{prel.}}$ obs./exp.</th>
<th>$W$ contrib. $e\mu (\tau)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full sample</td>
<td>25/18.4 ± 2.5</td>
<td>9/4.9 ± 0.8</td>
<td>5 / 5.81 ± 1.36</td>
<td>≈ 75(15)%</td>
</tr>
<tr>
<td>$P_T^{X} &gt; 25$ GeV</td>
<td>11/2.9 ± 0.6</td>
<td>6/2.9 ± 0.6</td>
<td>0 / 0.53 ± 0.10</td>
<td>≈ 85(50)%</td>
</tr>
</tbody>
</table>

**ZEUS 1994-2000**

<table>
<thead>
<tr>
<th>$\mathcal{L}(e^{\pm}p) = 130 \text{ pb}^{-1}$</th>
<th>Electron obs./exp.</th>
<th>Muon obs./exp.</th>
<th>Tau obs./exp.</th>
<th>$W$ contrib. $e\mu (\tau)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full sample</td>
<td>24 / 20.6 ± 3.2</td>
<td>12 / 11.9 ± 0.6</td>
<td>3 / 0.4 ± 0.12</td>
<td>≈ 17(48)%</td>
</tr>
<tr>
<td>$P_T^{X} &gt; 25$ GeV</td>
<td>2 / 2.9 ± 0.46</td>
<td>5 / 2.75 ± 0.21</td>
<td>2 / 0.2 ± 0.05</td>
<td>≈ 50(50)%</td>
</tr>
</tbody>
</table>

→ combined electron+muon (H1):

full sample : $34/23.3 \pm 3.2$ (73%)

$P_T^{X} > 25$ GeV : $17/5.8 \pm 1.1$ (84%)

= HERA I+II
**W production: \( W \rightarrow e \nu \)**

New ZEUS analysis (66 pb\(^{-1}\), e\(^+\)p, HERA I)

- **Graphic 1:**
  - **Y-axis:** Events
  - **X-axis:** \( \theta_e (\text{rad}) \)
  - **Legend:**
    - Black circles: ZEUS (Prel.) 99-00
    - Yellow: SM MC
    - Red: Signal MC

- **Graphic 2:**
  - **Y-axis:** Events
  - **X-axis:** \( P_T^e \) (GeV)

- **Arrow:** good understanding of detector
5 events found $\Rightarrow \sigma < 2.8$ pb at 95% CL
Summary

• **HERA** performs a wide range of analyses of electroweak physics
  • very good understanding of **NC** and **CC** cross section
  over more than 7 orders of magnitude!
  • measurement of W mass for t-channel W-exchange (unique at HERA)
  • remove LEP ambiguities for Zqq couplings
  • **lepton polarisation**: parity violation of **CC** interaction in agreement with **SM**
  • limit on **W production** cross section
  • Still very interesting excesses in \( e\nu + \mu\nu \) by **H1**, in \( \tau\nu \) by **ZEUS**
  and also in recent data \( e\nu \) by **H1**

⇒ more luminosity needed to solve “Isolated Lepton Puzzle”

Outlook

• **HERA** provides now \( e^-p \) collisions (only \( \approx 20 \text{ pb}^{-1} \) from 1998/99)

⇒ interesting potential for more “Electroweak Physics from HERA”
Backup
# Isolated Lepton Results at HERA I

<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{L}(e^\pm p) = 118$ pb$^{-1}$</td>
<td>$\mathcal{L}(e^\pm p) = 130$ pb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Full sample</td>
<td>11 / 11.5 ± 1.5</td>
<td>24 / 20.6 ± 3.2</td>
</tr>
<tr>
<td>$p_T^X &gt; 25$ GeV</td>
<td>5 / 1.76 ± 0.30</td>
<td>2 / 2.9 ± 0.46</td>
</tr>
<tr>
<td>$p_T^X &gt; 40$ GeV</td>
<td>3 / 0.66 ± 0.13</td>
<td>0 / 0.94 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>8 / 2.94 ± 0.50</td>
<td>12 / 11.9 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>6 / 1.68 ± 0.30</td>
<td>5 / 2.75 ± 0.21</td>
</tr>
<tr>
<td></td>
<td>3 / 0.64 ± 0.14</td>
<td>0 / 0.95 ± 0.12</td>
</tr>
<tr>
<td></td>
<td>5 / 5.81 ± 1.36</td>
<td>3 / 0.4 ± 0.12</td>
</tr>
<tr>
<td></td>
<td>0 / 0.53 ± 0.10</td>
<td>2 / 0.2 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>0 / 0.22 ± 0.05</td>
<td>1 / 0.07 ± 0.02</td>
</tr>
</tbody>
</table>

*W contribution is NLO: Diener, Schwanenberger, Spira*  

**Observed excesses in H1 + Zeus do not match channels**