Electroweak Physics at HERA

Joachim Meyer
DESY
The conference logo really fits this talk …….
Outline

Test of electroweak SM at high spacelike momentum transfers

HERA I:
- Electroweak Unification
- Electroweak DIS cross section fits
- Propagator mass
- NC quark couplings

HERA II:
- Polarized CC cross sections
- Polarized NC cross sections

Outlook
Inclusive Neutral Current (NC) & Charged Current (CC) Cross Sections

Structure Functions (SFs)

Electroweak Parameters

Polarization $P_e$ (HERA-II only)

Parton Distribution Functions (PDFs)

This talk
1993: Very first electroweak result at HERA from 0.3 pb⁻¹

HERA total CC cross section converted to equivalent neutrino cross section

First evidence of W-Propagator effect in Charged Current DIS
Measured NC and CC cross sections

HERA I Data 1994 – 2000  (100 pb⁻¹ per experiment)

Suppressed due to large mass of W boson compared to NC DIS

Electro-Weak unification at high $Q^2$

High $Q^2$ results statistics limited!
Kinematics:

Deep Inelastic Scattering at HERA

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

Virtuality of exchanged boson

Spatial resolution: \( \lambda \approx \frac{1}{\sqrt{Q^2}} \)

Momentum fraction of the struck quark

\[ x = \frac{Q^2}{2p \cdot q} \]

Inelasticity

\[ y = \frac{p \cdot q}{p \cdot k} \]

\[ s = (p + k)^2 \quad Q^2 = s \cdot x \cdot y \]

Neutral Current: exchange of \( \gamma \) or \( Z^0 \)

Charged Current: exchange of \( W^\pm \)

Only two independent
CC Cross Section

\[
\frac{d^2\sigma^{CC}(e^+p)}{dx dQ^2} = \frac{G_F^2}{4\pi} \frac{M_W^2}{M_W^2 + Q^2} \left[ u - c + (1 - y)^2 (d + s) \right]
\]

\[
\frac{d^2\sigma^{CC}(e^-p)}{dx dQ^2} = \frac{G_F^2}{4\pi} \frac{M_W^2}{M_W^2 + Q^2} \left[ u + c + (1 - y)^2 (d - s) \right]
\]

HERA Charged Current

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NC Cross Section

\[
\frac{d^2\sigma_{NC}(e^+p)}{dx dQ^2} = \frac{2\pi a^2}{xQ^4} \left[ Y_1 F_2^{NC} \mp Y_2 xF_3^{NC} - y^2 F_L^{NC} \right] \quad Y_\pm = 1 \pm (1 - y)^2
\]

- **Dominant contribution**
- **Contribution only important at high** \(Q^2\)
- **Sizeable only at high** \(y\)

**NC structure functions**, \(F_2^{NC}\) and \(xF_3^{NC}\), can be decomposed as

- \(\gamma\) exchange
- \(\gamma-Z\) interference
- \(Z\) exchange

\[
F_2^{NC} = F_2^\gamma - v_e K_Z F_2^Z + (v_e^2 + a_e^2) K_Z F_2^Z
\]

\[
xF_3^{NC} = a_e K_Z xF_3^Z + 2v_e a_e K_Z xF_3^Z
\]

**Experiment measures** Cross-Sections and extract SFs

**SFs**: coupling constant & Parton Distribution Functions (PDFs)
HERA-I Results: Combined EW+PDF Fit (H1)

The low $Q^2$ precision cross section data +
the high $Q^2$ NC $e^+p$ & $e^-p$ data +
the high $Q^2$ CC $e^+p$ & $e^-p$ data

5 sets of PDFs:

- gluon, up-type quark, down-type quark & their anti-quarks

- NC data at high $Q^2$ also sensitive to quark couplings to the $Z$ boson

- CC data also sensitive to $G$, $W$ propagator mass [model independent]
  $M_W$, $m_t$ [within the SM framework]

\[
\frac{d^2\sigma_{CC}(e^+p)}{dx dQ^2} = \frac{G_F^2 M_W^4}{2\pi x (Q^2 + M_W^2)^2} \Phi(\text{PDFs})
\]

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**Combined EW+PDF Analysis Strategies**

**Model independent fits:**

1) Fit $a_u - \nu_u - a_d - \nu_d$-PDF  
   to extract light quark couplings to the Z boson

2) Fit $G-M_{\text{prop}}$-PDF  
   to determine the normalization factor $G$ and W propagator mass $M_{\text{prop}}$

3) Fit $M_{\text{prop}}$-PDF  \([\text{fix } G \text{ to } G_F]\)  
   to determine the W propagator mass $M_{\text{prop}}$

**Fits within the SM framework:**

\[
G_F^2 = \frac{\pi \alpha}{\sqrt{2} M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right)} \frac{1}{1 - \Delta r}
\]

\(\Delta r\) contains - quadratic dependence on $m_t$  
- logarithmic dependence on $M_H$

4) Fit $M_W$-PDF  \([\text{fix } m_t \text{ to } 178\text{GeV}, M_H \text{ to } 120\text{GeV}]\)  
   to determine the SM W mass $M_W$

5) Fit $m_t$-PDF  \([\text{fix } M_W \text{ to } 80.425\text{GeV}, M_H \text{ to } 120\text{GeV}]\)  
   to determine the top quark mass $m_t$
First Results on Light Quark Couplings to Z at HERA

H1

CDF

LEP EWWG preliminary (Feb. 05)

v_u - a_u - v_d - a_d - PDF

68% CL

H1

CDF

LEP EWWG preliminary (Feb. 05)

v_u - a_u - v_d - a_d - PDF

68% CL

SM:

\[ v_q = I_q^3 - 2e_q \sin^2 \theta_W \]

\[ a_q = I_q^3 \]

Tevatron: \( q\bar{q} \rightarrow e^+e^- \) Drell-Yan, \( A_{FB} \):

LEP: \( e^+e^- \rightarrow q\bar{q}(\gamma) \) \([a^2_q + v^2_q]\):
http://lepewwg.web.cern.ch/LEPEWWG/plots/winter2005/

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With GF from PDG:

$$M_{\text{Prop}} = 82.9 \pm 1.9 \text{ GeV}$$

W Propagator Mass and Coupling

H1

$G (\text{GeV}^{-2})$

$M_{\text{prop}} (\text{GeV})$

68% CL

World Average

With $G_F$ from PDG:

$M_{\text{Prop}} = 82.9 \pm 1.9 \text{ GeV}$
Improved Precision on W Propagator Mass

HERA measurement of W propagator mass

H1 $e^+p$ 94-97
ZEUS $e^+p$ 94-97
H1 $e^-p$ 98-99
ZEUS $e^-p$ 98-99
ZEUS $e^+p$ 99-00
H1 94-00 (this analysis)

Mw (GeV)
Fits Imposing the SM Constraints

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

Introducing SM $G_F$-$M_W$ relation in On-Mass-Shell (OMS) scheme

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

Quadratic dependence on $m_t$  \hspace{1cm} Logarithmic dependence on $M_H$

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**Determination of SM Parameters**

- **W mass value:**
  \[ M_W = 80.786 \pm 0.205_{\text{exp}} \text{ GeV} \]
  
  + the world average \[ M_Z \]
  
  \[ \sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2} = 0.2151 \pm 0.0040_{\text{exp}} \]

Using \( M_W \) (PDG) restricts top quark mass

- \( m_t = 104 \pm 44_{\text{exp}} \text{ GeV} \)

  - First determination in DIS at EW scale

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HERA II

- Substantial increase in luminosity
- Longitudinally polarized lepton beams
Luminosity at HERA-II

High Luminosity → sensitivity in High-\(Q^2\) region

Luminosity used for physics analysis per experiment:
- HERA-I: 100\(\text{pb}^{-1}(e^+p)\), 20\(\text{pb}^{-1}(e^-p)\)
- HERA-II: 40\(\text{pb}^{-1}(e^+p)\), 100\(\text{pb}^{-1}(e^-p)\)

By the end of the HERA-II in July 2007, expect \(\sim 700\text{pb}^{-1}\) per experiment
### Data samples

**H1 data samples**

<table>
<thead>
<tr>
<th></th>
<th>$P &lt; 0$ (LH)</th>
<th>$P &gt; 0$ (RH)</th>
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<tbody>
<tr>
<td><strong>$e^+p$ data</strong></td>
<td>$L = 21.7 \text{ pb}^{-1}$</td>
<td>$L = 15.3 \text{ pb}^{-1}$</td>
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<tr>
<td></td>
<td>$P = -40.2 %$</td>
<td>$P = +33.0 %$</td>
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<tr>
<td><strong>$e^-p$ data</strong></td>
<td>$L = 17.8 \text{ pb}^{-1}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$P = -25.4 %$</td>
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**ZEUS data samples**

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<th>$P &lt; 0$ (LH)</th>
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</thead>
<tbody>
<tr>
<td><strong>$e^+p$ data</strong></td>
<td>$L = 16.4 \text{ pb}^{-1}$</td>
<td>$L = 14.1 \text{ pb}^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$P = -40.2 %$</td>
<td>$P = +31.8 %$</td>
</tr>
<tr>
<td><strong>$e^-p$ data</strong></td>
<td>$L = 35.3 \text{ pb}^{-1}$</td>
<td>$L = 6.5 \text{ pb}^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$P = -25.9 %$</td>
<td>$P = +29.2 %$</td>
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Charged current physics at HERA II
CC Total Cross-Section (H1)

Remind: CC is pure weak

\[ \sigma_{CC}(P_{e^\pm}) = (1 \pm P_{e^\pm})\sigma_{CC}(P_{e^\pm} = 0) \]

Direct observation of chiral structure of weak interaction

- A clear linear dependence is observed both \( e^+ \) and \( e^- \)
- Data are in agreement with the SM prediction

\[ \sigma_{CC}(P_e = +33\%) = 34.67 \pm 1.94(stat.) \pm 1.66(syst.) \text{ pb} \]

\[ \sigma_{CC}(P_e = -40\%) = 13.80 \pm 1.04(stat.) \pm 0.94(syst.) \text{ pb} \]

\[ \sigma_{CC}(P_e = -25\%) = 66.42 \pm 2.39(stat.) \pm 2.99(syst.) \text{ pb} \]
CC Total Cross-Section: H1 and ZEUS

$Q^2 > 400 \text{GeV}^2$, $y < 0.9$

Right Handed CC cross section is extrapolated by linear fit to H1+ZEUS $e^+p$ data

$\sigma_{e^+p \rightarrow \nu X}(P_{e^+} = -100\%) = 0.2 \pm 1.8(\text{stat.}) \pm 1.6(\text{syst.}) \text{ pb}$

Consistent with the SM prediction of: $\sigma_{CC}(RH) = 0$
The polarization dependence of CC – DIS scattering has already been measured in 1979 at the CERN Neutrino beam. (Phys.Lett. B86 ; 222 (1979))

Result:

The longitudinal Polarisation of the positive muons is

\[ P = + 1.09 \pm 0.22 \]

(at an average momentum transfer 3.2 GeV² !!!)
polarisation dependence seen not only total cross section but differential cross section in all kinematic regions
Neutral current physics
At HERA II
For NC: the electromagnetic contribution dominating at low $Q^2$ is independent of $P_e$. Weak NC only significant at high $Q^2$. 

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NC Differential Cross Section (ZEUS)

- $d\sigma/dQ^2$ for NC: Polarisation dependence is not observed conclusively with the current limited statistics
Outlook

HERA II is expected to deliver approx 700 pb\(^{-1}\) to each experiment. There will be an equal share of \(e^+\) and \(e^-\), left- and righthanded polarized.

More precise checks of electroweak SM possible:
- Better \(M_W\) determination (spacelike Propagator mass)
- More precise \(Z_0\) couplings to light quarks
HERA Physics workshop studies: W - Propagator Mass

H1 Result:

HERA I (100 pb\(^{-1}\), unpol.):

\[ M_{\text{prop}} = 82.9 \pm 1.9 \text{ GeV} \]

\[ M_W = 80.8 \pm 0.2 \text{ GeV} \]

Precise check of EW theory when combined with M_top from Tevatron (LHC)

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Polarised NC DIS cross section

\[
\frac{d^2\sigma^{NC} (e^\pm p)}{dx dq^2} = \frac{2\pi a^2}{xq^4} [H_0^\pm + P_e H_F^\pm]
\]

Unpolarised contribution

Polarised contribution: only includes \( \gamma \cdot Z \) and \( Z \) terms

\[
F_2^{NC} = F_2^\gamma - (v^\gamma - p, a_\gamma) K_z F_2^{ZL} + (v^\gamma + a_\gamma - 2p, v, a_1) K_z^2 F_2^Z
\]

\[
x F_3^{NC} = -(a, p, v) K_z x F_3^{ZL} + [2v, a_\gamma - (v^\gamma + a_\gamma)] K_z^2 x F_3^Z
\]

\[
[F_2, F_2^{ZL}, F_2^Z] = \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2] (q + \overline{q})
\]

\[
[x F_3^{ZL}, x F_3^Z] = 2\sum_q [e_q a_q, v_q a_q] (q - \overline{q})
\]

\[
K_z = \frac{1}{4\sin^2 \theta_W \cos^2 \theta_W} \frac{Q^2}{Q^2 + M_Z^2}
\]

Polarised e^\pm beam helps to constrain \( v_q \)
HERA Physics workshop studies: Light Quark Couplings to $Z_0$

H1 RESULT:

- Quark couplings can be accurately measured, e.g. light quark couplings by looking at differences between $\sigma(L,R)$.
- Great improvement over unpolarised case.
- $e_{L,R}^\pm$, $P = \pm 70\%$
- 250 pb$^{-1}$ per beam

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<th>$\nu$</th>
<th>$\alpha$</th>
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<tbody>
<tr>
<td>$u$</td>
<td>13%</td>
<td>6%</td>
</tr>
<tr>
<td>$d$</td>
<td>17%</td>
<td>17%</td>
</tr>
</tbody>
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Hera I (unpol):
$\alpha_u = 0.56 \pm 0.10$
$\nu_u = 0.04 \pm 0.19$

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Conclusion

• With approx. 200 pb\(^{-1}\) significant tests of the SM electroweak sector at high spacelike momentum transfers have been performed:
  - Electroweak unification, CC-Propagator mass,
  - Light quark Z\(_0\) couplings, CC-chiral structure,
  - NC polarisation dependences

• A factor 3 more luminosity still to come at HERA II and the availability of longitudinally polarized electrons and positrons will significantly enhance the sensitivity of these SM tests.
Despite ‘HERA is a QCD machine’ there are also interesting electroweak results which I hope justify the conference logo …

Many thanks for your attention

Thanks to my colleagues from Zeus and H1 for supplying some of these slides

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