Electroweak Measurements

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- Experimental framework (LEP, Tevatron, HERA)
- Precision tests
- Confrontation with lower energy data
- Weak boson production and properties
- Electroweak measurements in DIS at HERA
- Future
- Conclusions

Many thanks to:
Max Klein, Martin Grunewald, Pippa Wells, Dmitri Denisov, Jan Timmermans, Bolek Pietrzyk, Emmanuelle Perez, Matthew Wing, Richard Hawkings, David Waters, Chris Hays
Colliders at Fermi Scale

LEP

e⁺ e⁻ collider (2000)
$E_{cm} = 90\text{–}209 \text{ GeV}$
Lumi = 900 pb⁻¹/exp.(phys.)
ALEPH, DELPHI, L3, OPAL

HERA

$e^+ e^- p$ collider
$E_{cm} = 320 \text{ GeV}$
H1, ZEUS
HERA I 120 pb⁻¹/expt(phys.)
HERA II 2007 -> 700 pb⁻¹ (delivered, $e^\pm, \pm P_e$)

TEVATRON

$e^\pm p$ collider
$E_{cm} = 1.8 \text{ TeV}$
Run I
130 pb⁻¹/exp.(phys.)

-> pp collider: CDF, D0
Run II $E_{cm} = 1.96 \text{ TeV}$
1 fb⁻¹ delivered
2009 -> 4-8 fb⁻¹

SLC: polarized $e^+ e^-$ at Z peak

Many other interesting results from lower energy facilities
The masters of the EW sector: Z pole, W-pairs, final refined analysis still improve

ALEPH, DELPHI, L3, OPAL
L~ = 900 pb⁻¹/expt.

e⁺e⁻ → hadrons

Cross-section (pb)

Centre-of-mass energy (GeV)
Tevatron

$L(\text{deliv } 06/2005) \sim 1 \text{ fb}^{-1}$

$L(2009) = 4-8 \text{ fb}^{-1}$
HERA

Unique e(27 GeV) p(920 GeV) collider, \(E_{cm} = 320\) GeV

2 collider experiments **H1 and ZEUS**, HERMES(fixed target)

**HERA I** (1994-2000): for physics \(~120\) pb\(^{-1}\)/experiment

**HERA II** (since 2003): polarized e-beam in collision

\[L(\text{HERA II}): e^\pm p \text{ (phys.): } 100\ \text{pb}^{-1}\]

\[e^\pm \text{ polarization: } 25-40\%\]

2007: 700 pb\(^{-1}\) delivered
**Status of the SM**

http://lepewwg.web.cern.ch/LEPEWWG/
last update June 2005

- **Consistency check of the SM based on high precision measurements**

- More than 1000 data points combined in 17 observables calculated in the SM from:
  - $\alpha_{\text{em}}$ (precision $3 \times 10^{-9}$) the critical part $\Delta \alpha_{\text{had}}$ (from $\text{e}^+\text{e}^-\rightarrow \text{hadrons}$)
  - $G_F$ (precision $9 \times 10^{-6}$) ($\rightarrow \text{MW}$)
  - $M_Z$ (precision $2 \times 10^{-5}$) from lineshape (LEP-1)
  - $\alpha_s(M_Z)$ (precision $2 \times 10^{-2}$) hadronic observables
  - $M_{\text{top}}$ and $M_{\text{Higgs}}$

- **Zfitter 6.42, precision at 2 loop ($M_W$, $\sin^2\theta_W$) 3-loop for $\rho$**


Improved precision in final results from LEP collaborations
New input from low Q2 experiments very valuable
\[ \Delta \alpha_{\text{had}}^{5}(q^2) = -\frac{\alpha}{3\pi} q^2 \text{Re} \int \frac{R_{\text{had}}(s)}{s(s-q^2+i\varepsilon)} \, ds \]

New data from KLOE/CMD-2 (\(\rho\))

\[ \Delta \alpha_{\text{had}}^{5} \text{ used in the EW fit (small change)} \]

\[ \text{old value} \quad 0.02761 \pm 0.00036 \]

\[ \text{New value of } \Delta \alpha_{\text{had}}^{5} : 0.02758 \pm 0.00035 \]

\[ \text{error 0.9\% (was 2.3\%)} \]
Heavy Flavours: Final Results

- $R_b = \frac{\Gamma_b}{\Gamma_{\text{had}}}$
- $R_c = \frac{\Gamma_c}{\Gamma_{\text{had}}}$
- $A_{fb}(b) = \frac{3}{4} A_e A_b$
- $A_{fb}(c) = \frac{3}{4} A_e A_c$
- $A_b$
- $A_c$
- $\chi^2/\text{Ndof} = 53/(105-14)$

Central values very consistent
Asym. are statistics dominated
New top mass measurement

\( M_{\text{top}} \) (GeV):
old (2004): \( 178.0 \pm 4.2 \)
new (2005): \( 174.3 \pm 3.4 \)

(D0 run II in progress)

\( M_{\text{top}} \) error crucial for indirect \( M_{\text{higgs}} \) determination

\( M_{\text{higgs}} = 98^{+52}_{-26} \) GeV

\( M_{\text{higgs}} < 208 \) GeV @95% C.L.
### The EW fit: picture confirmed

#### Preliminary

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>2005</th>
<th>2004</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha_{\text{had}}^{(5)}(m_Z)$</td>
<td>$0.02758 \pm 0.00035$</td>
<td>0.02768</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>$91.1875 \pm 0.0021$</td>
<td>91.1874</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>$2.4952 \pm 0.0023$</td>
<td>2.4962</td>
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<tr>
<td>$\sigma_{\text{had}}^0$ [nb]</td>
<td>$41.540 \pm 0.037$</td>
<td>41.479</td>
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<tr>
<td>$R_1$</td>
<td>$20.767 \pm 0.025$</td>
<td>20.741</td>
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<tr>
<td>$A_{\text{fb}}^{0,1}$</td>
<td>$0.01714 \pm 0.00095$</td>
<td>0.01645</td>
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</tr>
<tr>
<td>$A_1(P_Z)$</td>
<td>$0.1465 \pm 0.0032$</td>
<td>0.1481</td>
<td></td>
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<tr>
<td>$R_b$</td>
<td>$0.21629 \pm 0.00066$</td>
<td>0.21573</td>
<td></td>
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</tr>
<tr>
<td>$R_c$</td>
<td>$0.1721 \pm 0.0030$</td>
<td>0.1723</td>
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<tr>
<td>$A_{\text{fb}}^{0,b}$</td>
<td>$0.0992 \pm 0.0016$</td>
<td>0.1038</td>
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<tr>
<td>$A_{\text{fb}}^{0,c}$</td>
<td>$0.0707 \pm 0.0035$</td>
<td>0.0742</td>
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<tr>
<td>$A_b$</td>
<td>$0.923 \pm 0.020$</td>
<td>0.935</td>
<td></td>
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<tr>
<td>$A_c$</td>
<td>$0.670 \pm 0.027$</td>
<td>0.668</td>
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<tr>
<td>$A_1(\text{SLD})$</td>
<td>$0.1513 \pm 0.0021$</td>
<td>0.1481</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{\text{fb}})$</td>
<td>$0.2324 \pm 0.0012$</td>
<td>0.2314</td>
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<td></td>
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<tr>
<td>$m_W$ [GeV]</td>
<td>$80.425 \pm 0.034$</td>
<td>80.383</td>
<td></td>
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<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>$2.133 \pm 0.069$</td>
<td>2.092</td>
<td></td>
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<tr>
<td>$m_t$ [GeV]</td>
<td>$174.3 \pm 3.4$</td>
<td>175.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Additional Data

- $\alpha_s(M_Z) = 0.1188 \pm 0.0027$
  - (PDG 2004: 0.1187 ± 0.0020)

- $N_{\nu} = 2.9840 \pm 0.0082$
Confrontation with low $Q^2$

- **APV Cs 0.4% ($Q^2=0$ GeV$^2$)**
  - $Q_{w}=-72.60\pm0.48$ (PDG2004)
  - $Q_{w}^{\text{SM}}=-72.94\pm0.04$
  - $Q_{w}^{Z,N}\simeq Z(1-4 \sin^2 \theta_w)-N$

- **E158 ($Q^2=0.036$ GeV$^2$)**
  - polarized $e^- e^-$ scattering
  - measure $A_{LR}$ deduce $\sin \theta_{\text{eff}}$
  - $\sin^2 \theta_{w}^{\text{eff}}(Q=0.6)=0.2397\pm0.0013$

- **NuTeV ($Q^2=\sim25$GeV$^2$):CC/NC in $\nu-N$**
  - $\sin^2 \theta_{w}^{3.0\sigma}$ from the SM

- **$a_{\mu}$: BNL($\mu^\pm$) @ 2.7$\sigma$**

\[(a_{\mu} - 11659000)\times 10^{-10} = 208 \pm (5 \text{ stat.} + 4 \text{ syst.}) \]
\[(a_{\mu} - 11659000)\text{th} \times 10^{-10} = 183 \pm 7 \quad \text{[e+e-] DEHZ04} \]
Running of $\alpha^{\text{em}}$ at low energy

Measure the dependence $\sigma(t)$ using the luminometers (only scaling, not the absolute value)

$$\Delta \alpha(-6.07 \text{ GeV}^2) - \Delta \alpha(-1.81 \text{ GeV}^2) = (440 \pm 58 \pm 43 \pm 30) \times 10^{-5}$$

$$\Delta \alpha_{\text{had}}(-6.07 \text{ GeV}^2) - \Delta \alpha_{\text{had}}(-1.81 \text{ GeV}^2) = (237 \pm 58 \pm 43 \pm 30) \times 10^{-5}$$

Direct evidence for $\alpha$ running (>5 $\sigma$); hadronic contribution to running (3$\sigma$)
W pair production: the LEP harvest

Gauge structure of the SM
A rich sample of W's (O(10^4)/expt.)

![LEP Preliminary Graph](image)

- **σ_{WW} (pb)**
- **√s (GeV)**

**Models:**
- YFSWW/RacoonWW
- no ZWW vertex (Gentle)
- only ν_e exchange (Gentle)

**Date:** 17/02/2005
W/Z boson production at Tevatron

Leptonic decay modes of W and Z (e, μ, τ)

\[ \sigma(E) \text{ consistent with the theoretical prediction (NNLO)} \]


Large sample available for the study of W properties
**W Mass and branching ratios**

### W-Boson Mass [GeV]

- **TEVATRON (Run I)**: $80.452 \pm 0.059$
- **LEP2**: $80.412 \pm 0.042$
- **Average**: $80.425 \pm 0.034$ ($\chi^2/DoF = 0.3/1$)
- **NuTeV**: $80.136 \pm 0.084$
- **LEP1/SLD**: $80.363 \pm 0.032$
- **LEP1/SLD/$m_t$**: $80.373 \pm 0.023$

New published OPAL: $M_W = 80.415 \pm 0.052$
(preliminary error was 67 MeV)

Analysis in progress at Tevatron Run II:
$M_W, Br(W \to \tau)$

### W Leptonic Branching Ratios

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$Br(W \to \nu\nu)$</th>
<th>$Br(W \to e\nu)$</th>
<th>$Br(W \to \mu\nu)$</th>
<th>$Br(W \to \tau\nu)$</th>
<th>$Br(W \to l\nu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>$10.78 \pm 0.29$</td>
<td>$10.65 \pm 0.17$</td>
<td>$10.59 \pm 0.15$</td>
<td>$11.44 \pm 0.22$</td>
<td>$10.84 \pm 0.09$</td>
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<tr>
<td>DELPHI</td>
<td>$10.55 \pm 0.34$</td>
<td>$10.65 \pm 0.27$</td>
<td>$11.46 \pm 0.43$</td>
<td>$11.89 \pm 0.45$</td>
<td>$11.44 \pm 0.22$</td>
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<tr>
<td>L3</td>
<td>$10.78 \pm 0.32$</td>
<td>$10.87 \pm 0.26$</td>
<td>$11.64 \pm 0.39$</td>
<td>$11.96 \pm 0.34$</td>
<td>$11.44 \pm 0.22$</td>
</tr>
<tr>
<td>OPAL</td>
<td>$10.40 \pm 0.35$</td>
<td>$10.55 \pm 0.34$</td>
<td>$11.64 \pm 0.39$</td>
<td>$11.96 \pm 0.34$</td>
<td>$11.44 \pm 0.22$</td>
</tr>
</tbody>
</table>

Winter 2005 - LEP Preliminary
ALEPH, DELPHI, L3 final, OPAL prel.

**BR(W->qq)=67.48 \pm 0.28**
W boson width

Direct measurement from $M_T$ fit

New preliminary result D0 RunII 177 pb$^{-1}$:
$2.011 \pm 0.093_{\text{stat}} ^{0.099}_{\text{syst}}$

CDF RunII (72 pb$^{-1}$)
$2.079 \pm 0.041$

Indirect determination at Tevatron from W/Z cross section ratio

CDF RunII (72 pb$^{-1}$)
$2.079 \pm 0.041$

e\(^+\)e\(^-\) events at Tevatron

Drell-Yan: \(qq \rightarrow e^+e^-\), measures \(\gamma Z\) interference, \(A_{FB} = f(M_{ee})\)

sensitive to \(\sin^2\theta_W^{\text{eff}}\), quark couplings and new physics

CDF

\[
\sin^2\theta_W^{\text{eff}} = 0.2238 \pm 0.0040(\text{stat}) \pm 0.0030(\text{syst})
\]

(EW Fit: 0.2314)

Rev. D 71, 052002 (2005)
Single boson production at LEP

Rare processes: Cross section $< 1$ pb statistically limited, in agreement with the SM
Di-boson production at Tevatron

EW processes are “weak” but rich topologies
Irreducible background for searches:
→ anomalous couplings or higgs

WZ+ZZ production:

D0: 0.3 fb\(^{-1}\) (run II)
3 events obs. / 0.7±0.1 (exp.)
\(\sigma < 13.3\) pb @ 95% CL

CDF 0.2 fb\(^{-1}\) (run II) Phys. Rev. D 71, 091105 (2005)
3 events obs. / 1.0±0.2 (exp.)
\(\sigma < 15.2\) pb @ 95% CL

\(\sigma_{SM} = 5.0\pm0.4\)
**Single W production at HERA**

- **Events with isolated leptons and $P_T^{miss}$**
- **$X$ section $\approx 1$ pb => $O(10^2)$ events/expt. at HERA I+II**
- **Events with large hadronic momentum observed by H1**

$P_{TX}>25$ GeV

**H1 (update)**  
(211 pb$^{-1}$) 17 / 6.4±1.1 (e,μ)  
HERA I and II data

**ZEUS (new analysis)** (106 pb$^{-1}$) 1/ 1.5±0.2 (e only)  
previous search (130pb$^{-1}$,HERA I) 7/5.7 (e,μ) (W:45%)

No deviation observed by ZEUS with present lumi

More $\int \mathcal{L}$ necessary
DIS at HERA

Charged Current (CC)

Neutral Current (NC)

\[ Q^2 \sim M_{W,Z}^2 \text{ (EW regime)} \]

\[ r_{\text{quark}} < 10^{-18} \text{m} \]

"p"/1000

HERA I data

ZEUS

H1
Proton structure and EW effects from DIS

- $Q^2 = -(k - k')^2 = -q^2$ boson virtuality
- $x = \frac{Q^2}{2P \cdot q}$ quark p momentum fraction
- $y = \frac{P \cdot q}{P \cdot k}$ inelasticity

Only 2 independent $Q^2 = s x y$

\[
\frac{d^2 \sigma_{NC}^{e^p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[ Y_+ \tilde{F}_2(x, Q^2) + Y_- x \tilde{F}_3(x, Q^2) \right]
\]

\[
Y_\pm \equiv 1 \pm (1 - y)^2
\]

\[
x \tilde{F}_3 \equiv -a_e \frac{\kappa Q^2}{(Q^2 + M_Z^2)} xF_3^{\gamma Z} + (2\nu_e a_e) \left( \frac{\kappa Q^2}{Q^2 + M_Z^2} \right)^2 xF_3^{\gamma Z}
\]

\[
[x F_3^{\gamma Z}, x F_3^{\gamma Z}] = 2x \sum_q [e_q a_q, \nu_q a_q] \{ q - \bar{q} \}
\]

HERA Neutral Current at high $x$

HERA experiments constrain parton distributions
CC [pure weak process] => resolve quark flavours
NC also sensitive to electroweak effects at high Q2
Combined EW-QCD fits

New approach (H1): common fit EW+QCD;
- use CC/NC HERA I data (>600 measurements)
- Fit: Structure Functions $\oplus$ EW\textsubscript{parameters}

First example: CC Propagator Mass measurement

\[
\frac{d^2\sigma^{\pm}_{\text{CC}}}{dx dq^2} = \frac{G_F^2}{2\pi x} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \Phi_{\text{CC}}
\]

Normalisation (includes rad.corr.)

Propagator Mass

\[M_W^{\text{prop}} = 82.87 \pm 1.82(\text{exp})^{+0.30}_{-0.16}(\text{mod}) \text{ GeV}\]

- model independent $M_{\text{boson(W)}}$ measurement
- unique using HERA t-channel exchange
On Mass Shell scheme

- $\alpha, M_W, M_Z \Rightarrow G_F(M_W)$
- Radiative corrections computed in SM
- $M_W$ is a parameter, dependent on $M_{H,\text{top}}$

$M_W = 80,709\pm 0,205(\text{exp})^{+0,048}_{-0,029}(\text{mod})\pm 0,025(\text{top})\pm 0,033(\text{th}) - 0,084(\text{Higgs})$ GeV

$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_{W^2}}$

$\sin^2 \theta_W = 0.2151 \pm 0.0040_{\text{exp.}}^{+0.0019}_{-0.0011}|_{\text{th}}$

EW fit : $0.2228 \pm 0.0003$

First determination in DIS @ EW scale
Light quarks couplings to the Z

- **b,c couplings very well known** (few % LEP from $A_{FB}(c,b)$)
- **Light quarks (u,d) couplings determination**
  - HERA: eq->eq Combined fit Z couplings + PDF
  - LEP : ee--->qq at Z peak ($a^2v^2$, $a^2+v^2$)
  - TEVATRON: qq->ee from Drell-Yan (electrons) $A_{FB}$
HERA II results with polarized beams

HERA can run with $e^\pm$ and both e-beam polarisations ($P=0.25-0.4$)

$$\sigma^{e^\pm}_P(P) = (1 \pm P)\sigma^{e^\pm}_{P=0}$$

CC: linear dependence established in DIS at HERA

Compatible with V-A structure (no RH currents)

CHARM (1979):
$$\nu_\mu N \rightarrow \mu X$$

It may be concluded that positive muons produced by interactions of high-energy antineutrinos with nuclei have a longitudinal polarization oriented along their momentum direction. Within the experimental errors the helicity is found to be $+1$, consistent with a purely $V_A$ form of the interaction. An upper limit
The future of precision EW measurements at high energy

- **LHC** ($E_{cm}=14\text{TeV}$) large statistics:
  - generous cross sections $W,Z,\text{top}$
  - $2.10^6$ $W$'s for 0.1 fb$^{-1}$
  - top, triple/quartic gauge couplings,...

- **LC (GigaZ or $E_{cm}=1$ TeV) interplay:**

<table>
<thead>
<tr>
<th>now</th>
<th>Tev. Run II</th>
<th>LHC</th>
<th>LC</th>
<th>GigaZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta \sin^2 \theta_{\text{eff}} \times 10^6$</td>
<td>17</td>
<td>78</td>
<td>14–20</td>
<td>(6)</td>
</tr>
<tr>
<td>$\delta M_W \ [\text{MeV}]$</td>
<td>34</td>
<td>27</td>
<td>15</td>
<td>10</td>
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<tr>
<td>$\delta m_t \ [\text{GeV}]$</td>
<td>5.1</td>
<td>2.7</td>
<td>1.0</td>
<td>0.2–0.1</td>
</tr>
<tr>
<td>$\delta m_h \ [\text{MeV}]$</td>
<td>—</td>
<td>—</td>
<td>200</td>
<td>50</td>
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</tbody>
</table>

hep-ph/0410364
Conclusions

- SM is in good shape
  - new physics is not (yet) on the SM territory
  - a few peculiarities $2.5-3\sigma$ ($A_{fb}(b)$, $N_\nu$, NuTeV, $\text{Br}(W\to\tau)$, $a_\mu$)

- LEP is finalizing results:
  - improving in precision amazing and worth the effort

- Tevatron is refining the analysis of Run II data
  - increase in the luminosity will improve the precision.

- HERA: a first coherent QCD+EW analysis of DIS data
  - increase luminosity, $e^\pm$-beam polarization

- Precision measurement will continue soon at LHC and (latter) at the LC
Polarisation effects in NC-DIS

- NC(P_\text{e}) via parity violating couplings of the Z in the t-channel
- The effect is not yet established experimentally
- Improvement in L/P will improve the outcome for NC's
  - (q densities, couplings)