LEP/SLC retrospective and status of global electroweak fits

Doreen Wackeroth
SUNY at Buffalo

1. A brief history of the LEP and SLC experiments
2. Precision tests of the Standard Model (SM) of particle physics
3. The search for the SM Higgs boson
4. “New physics”?
5. Outlook

1. A brief history of the LEP and SLC experiments

1989: CERN’s Large Electron Positron (LEP) collider starts operation.

LEP-I (1990-1995):

LEP produces about 20 million Z bosons in unpolarized $e^+e^-$ collisions, and the four detector collaborations take data at energies at and around the Z resonance, $|\sqrt{s} - M_Z| = 1.8, 3$ GeV.

Z-pole measurements include hadronic and leptonic cross sections, asymmetries, Z partial widths, and the $q\bar{q}$ charge asymmetry.

Z boson properties (mass, width) and $Zf\bar{f}$ couplings are precisely measured.
LEP-II (1996-2000): LEP increases the beam energy above the W-pair production threshold up to $\sqrt{s} = 209$ GeV:

\[
\begin{align*}
\text{Di-fermion cross sections, di-photon production, forward-backward asymmetries, and gauge boson pair (and single) production cross sections.}
\end{align*}
\]

W boson properties (mass, width) and electroweak gauge boson self couplings are precisely measured.

The LEP-II collaborations directly searched for the SM Higgs boson, mainly in $e^+e^- \rightarrow ZH \rightarrow f\bar{f}b\bar{b}$ up to Higgs masses of $M_H \approx \sqrt{s_{\text{max}}} - M_Z \approx 118$ GeV.

2000: LEP is dismantled to make room for the Large Hadron Collider (LHC).

LEP-II data are still being analysed and some results are still preliminary and continuously updated (e.g., W mass, triple and quartic electroweak gauge couplings, new physics searches).
The LEP collider ring (27 km) at CERN, Geneva, Switzerland
Future site of the Large Hadron Collider (LHC)
The LEP tunnel with four $e^+e^-$ interaction regions and detectors:

**ALEPH, DELPHI, L3, OPAL**

Illustration of the extraction of $Z$ lineshape parameters from the cross section to $e^+e^- \to Z \to \text{hadrons}$:

\[
\sigma(s) \propto \sigma^0 \frac{s \Gamma_Z^2}{(s - M_Z^2)^2 + (s \Gamma_Z)^2 / M_Z^2}
\]
1989: SLAC’s Linear $e^+ e^-$ Collider (SLC) starts operation.

SLC (1992-1998): The SLAC Large Detector (SLD) observes over 500K Z bosons in the collision of polarized $e^-$ (typically up to 75%) and unpolarized $e^+$. SLD provides the most precise single measurement of $\sin^2 \theta_{eff}^{lept}$ extracted from the polarized leptonic left-right asymmetry.

Most of the analysis of the SLD data has been finalized.

The SLC with one $e^+e^-$ interaction region and detector: SLD

1992-1998 Z yields with polarized electrons ($P_{e^-}$ in %):
The LEP/SLC (and Tevatron) success story

LEP/SLC succeeded in probing the electroweak sector of the SM at an unprecedented level of precision, with many observables being sensitive to genuine electroweak loop effects.

Many LEP/SLC observables are sensitive to loop effects induced by either undiscovered sectors of the SM (Higgs sector) or new particles of physics beyond the SM.

LEP/SLC collaborations found no compelling signal of new physics and succeeded in strongly constraining the parameters of a number of new models (e.g., Technicolor, SUSY).

LEP/SLC collaborations (together with CDF/D0 measurements of $m_t$, $M_W$) succeeded in deriving an indirect upper limit on the SM Higgs boson mass through its presence in quantum loops contributing to electroweak precision observables: $M_H < 211$ GeV (95% C.L.). LEPEWWG Winter 2003

If it’s there, it might be just around the corner ...
At LEP-II, a few spectacular SM Higgs candidates have been recorded (ALEPH, 4-jet events, > 206 GeV) consistent with $M_H$ around 116 GeV, but no discovery can be claimed.

$$Q(M_H) = \mathcal{L}(s + b)/\mathcal{L}(b)$$

The LEP-II Higgs search resulted in a lower bound on the Higgs boson mass of $M_H = 114.4$ GeV (95 % C.L.). The LEP Higgs WG, LHWG Note/2002-01
Thanks to LEP/SLC and the Tevatron ($M_W, m_t$), we can be confident that the SM, as a fully fledged quantum field theory and based on the gauge principle, correctly describes electroweak interactions among fundamental particles at presently accessible energies.

However, the jury is still out on spontaneous symmetry breaking as the mechanism responsible for the generation of $W, Z$ boson masses.
2. Precision tests of the Standard Model (SM) of particle physics

**The method**

**Experiment:**
20 precision (pseudo) observables have been extracted from the data collected at and around the Z-pole (SLD, LEP-I):

- Z lineshape and leptonic forward-backward asymmetries: $M_Z, \Gamma_Z, \sigma_{h_{ad}}^{0}, R_l, A_{fb}^{0,l}$
- Polarized lepton asymmetries: $A_l(P_\tau), A_l(SLD)$
- Heavy flavor results: $R_b, R_c, A_{fb}^{0,b}, A_{fb}^{0,c}, A_b, A_c$
- Hadronic charge asymmetry: $\sin^2 \theta_{eff}^{lep}(Q_{fb})$

and from other experiments:

- W mass and width (LEP-II, Tevatron): $M_W, \Gamma_W$
- Top-quark mass (Tevatron): $m_t$
- Atomic parity violation (Caesium): $Q_W(Cs)$
- Hadronic vacuum polarization: $\Delta \alpha_{had}^{(5)}$
- NuTeV: $\sin^2 \theta_W (\rightarrow M_W)$

The experimental precision is at the per-mille level probing the SM down to distances of $10^{-17}$ m.
(Pseudo-)Observables around the Z resonance  D.Bardin et al., hep-ph/9902452

Pseudo-observables are extracted from “real” observables (ROs) (cross sections, asymmetries) by de-convoluting them of QED and QCD radiation and by neglecting terms ($\mathcal{O}(\alpha \Gamma_Z/M_Z)$) that would spoil factorization ($\gamma$, $Z$ interference, $t$-dependent radiative corrections).

The $Z f \bar{f}$ vertex is parametrized as $\gamma_\mu \left( G^f_V + G^f_A \gamma_5 \right)$ with imaginary formfactors $G^f_{V,A}$, so that the partial Z width reads:

$$\Gamma_f = 4N_c \Gamma_0 (|G^f_V|^2 R^f_V + |G^f_A|^2 R^f_A) + \Delta_{EW/QCD}$$

$R^f_{V,A}$ describe QED,QCD radiation and $\Delta$ non-factorizable radiative corrections. Pseudo-observables are then defined as ($g^f_{V,A} = \text{Re} G^f_{V,A}$)

- $\sigma^0_h = 12\pi \frac{\Gamma_0 \Gamma_e}{M_Z^2 \Gamma_Z^2}$, $R_{q,l} = \frac{\Gamma_q, h}{\Gamma_h, l}$
- $A^f_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \rightarrow A^f,0_{FB} = \frac{3}{4} A_e A_f$, $A_f = 2 \frac{g^f_V g^f_A}{(g^f_V)^2 + (g^f_A)^2}$
- $A_{LR}(SLD) = \frac{N_L - N_R}{N_L + N_R} \frac{1}{<P_e>} \rightarrow A^0_{LR}(SLD) = A_e$

and $4|Q_f| \sin^2 \theta^f_{eff} = 1 - \frac{g^f_V}{g_A}$. 
New developments since summer 2002: new ALEPH $M_W$ measurement (included in fit), new D0 RUN-I $m_t$ measurement (not included, see, e.g., J.Estrada, procs. of HCP 2002)

Theory:
To at least match (better: exceed) the experimental precision, theoretical predictions need to go beyond the leading order and even beyond leading universal corrections (e.g., QED, running of $\alpha$).

Theory predictions for pseudo-observables are obtained with ZFITTER and TOPAZ0 including radiative corrections up to two loop (electroweak) and three loop (QED), using the following set of input parameters

$$\Delta \alpha_{had}^{(5)}, \alpha_s(M_Z), M_Z, m_t, M_H, G_\mu$$

New developments since summer 2002: progress in theoretical prediction for $Q_W$ (included in fit, A.I.Milstein et al. (2002)).

Status:
Complete 2-loop electroweak corrections to Z observables are not available, but highly desirable (LEP:$\sin^2 \theta_{eff}^{lep}$, GigaZ).

We will also need the corresponding 2-loop corrections to $\sin^2 \theta^\text{lept}_{\text{eff}}$.

Complete electroweak one-loop corrections to $W$-pair production are known in double-pole approximation. A.Denner et al., S.Jadach et al., G.Passarino al. procs. of LEP2 workshop

A careful (re-)evaluation of the theoretical uncertainties (due to missing higher order corrections, uncertainty of input parameters) is needed. see, e.g., G.Passarino’s transparencies of the Zeuthen workshop, Feb. 2003
By comparing measurements and theoretical predictions of electroweak precision observables

- the electroweak sector of the SM is probed at the quantum-loop level,
- the consistency of the SM is checked by comparing direct with indirect determinations of input parameters, e.g., $m_t$, $M_W$,
- the SM Higgs boson mass can be predicted, and
- the parameters of models beyond the SM can be constrained.
The leptonic and hadronic effective couplings to the Z boson
The global SM fit to all electroweak data:

Two $\sim 3\sigma$ “anomalies”:

$A_{FB}^{0,b}$, $\sin^2 \theta_W$ (NuTeV)

Possible sources:

- statistical fluctuation
- experimental systematics
- theoretical uncertainties
- non-standard physics (“tough”, e.g., the MSSM does not help)

Without NuTeV:

$\chi^2 / n.d.o.f = 16.7/14(27.3\%)$
Effective NC quark couplings in Neutrino-Nucleon scattering (NuTeV)

G.P.Zeller et al. (NuTeV), hep-ex/0110059, www.pas.rochester.edu/~ksmcf/NuTeV/, hep-ex/0203004

\[
\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}
\]
\[
\Rightarrow M_W = 80.136 \pm 0.084 \text{ GeV}
\]

Number of (light) neutrinos:
\[
N_\nu (LEP/SLD) = 2.9841 \pm 0.0083
\]
LEP-II: W-pair production

\[
\sqrt{s} \text{ (GeV)}
\]

\[
\sigma_{WW} \text{ (pb)}
\]

Winter 2003 - LEP Preliminary

ALEPH [1996-2000] \(80.379 \pm 0.058\)

DELPHI [1996-2000] \(80.404 \pm 0.074\)

L3 [1996-2000] \(80.376 \pm 0.077\)

OPAL [1996-1999] \(80.490 \pm 0.065\)

LEP \(80.412 \pm 0.042\)

\[\chi^2/dof = 29.6/37\]

LEP working group
**Measured $\sigma^{WW}$ / YFSWW**

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Measured $\sigma^{WW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>183</td>
<td>1.026 ± 0.024</td>
</tr>
<tr>
<td>189</td>
<td>0.982 ± 0.014</td>
</tr>
<tr>
<td>192</td>
<td>1.010 ± 0.030</td>
</tr>
<tr>
<td>196</td>
<td>1.031 ± 0.020</td>
</tr>
<tr>
<td>200</td>
<td>0.992 ± 0.019</td>
</tr>
<tr>
<td>202</td>
<td>1.006 ± 0.026</td>
</tr>
<tr>
<td>205</td>
<td>0.979 ± 0.019</td>
</tr>
<tr>
<td>207</td>
<td>1.009 ± 0.016</td>
</tr>
</tbody>
</table>

**Measured $\sigma^{WW}$ / RacoonWW**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>183</td>
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</tr>
<tr>
<td>189</td>
<td>0.984 ± 0.014</td>
</tr>
<tr>
<td>192</td>
<td>1.013 ± 0.030</td>
</tr>
<tr>
<td>196</td>
<td>1.033 ± 0.020</td>
</tr>
<tr>
<td>200</td>
<td>0.994 ± 0.019</td>
</tr>
<tr>
<td>202</td>
<td>1.009 ± 0.026</td>
</tr>
<tr>
<td>205</td>
<td>0.981 ± 0.019</td>
</tr>
<tr>
<td>207</td>
<td>1.013 ± 0.016</td>
</tr>
</tbody>
</table>

**LEP combined**

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Measured $\sigma^{WW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP combined</td>
<td>0.997 ± 0.011</td>
</tr>
</tbody>
</table>

**TGC parameters at 68 % CL:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>exp.</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_1^Z$</td>
<td>$0.998^{+0.023}_{-0.025}$</td>
<td>1</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>$0.943 \pm 0.055$</td>
<td>1</td>
</tr>
<tr>
<td>$\lambda_\gamma$</td>
<td>$-0.020 \pm 0.024$</td>
<td>0</td>
</tr>
</tbody>
</table>

**Exceptional agreement with the SM**

When only incl. universal leading ewk corr.

$\sigma^{WW}$ is about 2% higher ⇒

Experimental evidence for genuine, non-universal electroweak corrections.
2. The Search for the Higgs boson

The Higgs boson – a direct consequence of $W$ and $Z$ boson mass generation in the Standard Model via spontaneous symmetry breaking of the SU(2)$_L \otimes$ U(1)$_Y$ gauge group. Goldstone (1961); Goldstone, Salam and Weinberg (1962); Higgs (1964,1966); Kibble (1967); Brout and Englert (1964); Guralnik, Hagen and Kibble (1964)

The Higgs particle so far eluded direct observation.

<table>
<thead>
<tr>
<th>Where is the SM Higgs ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>We know from direct (LEP2) and indirect searches (EWK fits) that</td>
</tr>
<tr>
<td>114.4 GeV &lt; $M_H$ (\lesssim) 211 GeV (95 % C.L.)</td>
</tr>
<tr>
<td>$M_H$ (\lesssim) 180 GeV</td>
</tr>
<tr>
<td>(95 % C.L. with 10 fb$^{-1}$, 3 $\sigma$ discovery with 25 fb$^{-1}$)</td>
</tr>
</tbody>
</table>
Indirect searches via presence in loops, $M_W - M_Z$ correlation:

\[
M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi \alpha(0)}{\sqrt{2} G_{\mu} (1 - \Delta r(M_W, m_t, M_H, \ldots))}
\]

Direct and indirect measurements of $M_W$ are in good agreement:

- $M_W$ (LEP, $p\bar{p}$) = 80.426 ± 0.034 GeV
- $M_W$ (LEP/SLD) = 80.373 ± 0.033 GeV

- $M_W$ (LEP, $p\bar{p}$) prefers a light Higgs
- $M_W$ (NuTeV) prefers a heavy Higgs

\[
\delta m_t = 5 \text{GeV} \rightarrow \delta M_W \text{(LEP/SLD)} = 32 \text{ MeV}
\]

\[
\delta \Delta \alpha_{\text{had}} = 0.0002 \rightarrow \delta M_W = 3.7 \text{ MeV}
\]
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$ extracted from LEP/SLC asymmetries

Final

$A_{ib}^{0,l}$

$0.23099 \pm 0.00053$

$A_l$(SLD)

$0.23098 \pm 0.00026$

$A_l$(P$_\tau$)

$0.23159 \pm 0.00041$

$<Q_{ib}>$

$0.2324 \pm 0.0012$

Preliminary

$A_{ib}^{0,b}$

$0.23217 \pm 0.00031$

$A_{ib}^{0,c}$

$0.23206 \pm 0.00084$

Average

$0.23148 \pm 0.00017$

$\chi^2$/d.o.f.: 10.2 / 5

Spread in $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ due to $A_{FB}^{0,b}, A_l$(SLD)

lept. asymmetries: Higgs light

$b$ asymmetry: Higgs heavy

$\Delta \alpha_{\text{had}} = 0.02761 \pm 0.00036$

$m_Z = 91.1875 \pm 0.0021 \text{ GeV}$

$m_t = 174.3 \pm 5.1 \text{ GeV}$

$\Delta \alpha^{(5)} = 0.2324 \pm 0.0012$

$\Delta \alpha^{(5)} = 0.2340 \pm 0.0008$

$\Delta \alpha^{(5)} = 0.2345 \pm 0.0006$

$\Delta \alpha^{(5)} = 0.2348 \pm 0.0005$

$\Delta \alpha^{(5)} = 0.2351 \pm 0.0004$

$\Delta \alpha^{(5)} = 0.2354 \pm 0.0004$
LEPEWWG Winter 2003

**Higgs sensitivity of ewk observables**

Fitted value of $M_H$ strongly depends on $M_W$, $m_t$: shift of 5 GeV in $m_t \Rightarrow 35\%$ shift in $M_H$

M. Grünwald, ICHEP 2002
From global fit to all electroweak precision data:


\[ M_H = 91^{+58}_{-37} \text{ GeV} \ ; \ M_H < 211 \text{ GeV (95\% C.L.)} \]

**LEPEWWG Winter 2003**

- **blue band**: theoretical uncertainty due to missing higher order corrections
- **blue/red curves**: uncertainty due to \( \Delta \alpha_{\text{had}}^{(5)} \)

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D. Wackeroth, SUNY at Buffalo

APS/DPF 2003 Meeting

04/07/03
At LEP and SLC no compelling evidence for new physics has been found.

But:

- the minimal supersymmetric SM (MSSM) fits the electroweak precision data as well as the SM see, e.g. W.de Boer, C.Sander, and

- the present high central value of $M_W$ is in better agreement with the MSSM prediction of $M_W$.

However, the MSSM does not help to reduce the exp.-theo. discrepancy in $A_{fb}^{0,b}$.

LEP/SLC searches include: MSSM, excited fermions, LQ, single top (FCNC), exotic Higgs, $H^{++}$, $Z'$, extra dimensions, ...

For constraints on parameters of models beyond the SM from LEP/SLC data, please visit lepsusy.web.cern.ch/lepsusy/, lepexotica.web.cern.ch/LEPEXOTICA/.
The $M_W - M_Z$ correlation within the MSSM:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi \alpha(0)}{\sqrt{2} G_\mu \left(1 - \Delta r(M_W, m_t, M_{SUSY}, \ldots)\right)}$$

courtesy of S. Heinemeyer, W. Hollik and G. Weiglein:
An example:
LEP-II with $\sqrt{s} = 183 - 208$ GeV data

LEPSUSYWG. lepsusy.web.cern.ch. Summer 2002

CDF Collaboration, hep-ex/0106001, D0 Collaboration, hep-ex/9902013
Outlook

In the not so far future we can look forward to

- an improved extraction of $M_W$ (35 MeV) and of the triple and quartic electroweak gauge boson couplings from LEP-II data,
- a reduction of the uncertainty of $\Delta\alpha_{\text{had}}^{(5)}$ (more low energy data for $R(s)$)
- improved $m_t$, $M_W$ measurements and an independent measurement of $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ at the Tevatron Run-II.

<table>
<thead>
<tr>
<th>uncertainty</th>
<th>now</th>
<th>Tev. Run IIA</th>
<th>Run IIB</th>
<th>Run IIB*</th>
<th>LHC</th>
<th>LC</th>
<th>GigaZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta \sin^2 \theta_{\text{eff}} (\times 10^5)$</td>
<td>17</td>
<td>78</td>
<td>29</td>
<td>20</td>
<td>14–20</td>
<td>(6)</td>
<td>1.3</td>
</tr>
<tr>
<td>$\delta M_W$ [MeV]</td>
<td>34</td>
<td>27</td>
<td>16</td>
<td>12</td>
<td>15</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>$\delta m_t$ [GeV]</td>
<td>5.1</td>
<td>2.7</td>
<td>1.4</td>
<td>1.3</td>
<td>1.0</td>
<td>0.2</td>
<td>0.13</td>
</tr>
<tr>
<td>$\delta M_H / M_H$ [%]</td>
<td>58</td>
<td>35</td>
<td>25</td>
<td>23</td>
<td>18</td>
<td>14</td>
<td>8</td>
</tr>
</tbody>
</table>

(from all data)

from U.Baur et al. (Snowmass 2001), RUN IIA,IIB,IIB*:2,15,30 fb$^{-1}$

Stay tuned!