A Decade of Precision Electroweak Measurements

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Of the two fundamental interactions seen only in microscopic physics

- the strong and weak interactions -

the weak interaction was for a long time the most mysterious
but the basic ingredients of the weak interaction have slowly been built up:

- parity violation
- "V - A"
- W boson
- Z boson
- neutral currents

Standard Model:

- Glashow, Weinberg, and Salam
- `t Hooft, Veltman, and Lee
Ingredients of the Standard Model:

underlying SU(2) × U(1) gauge symmetry

\[ \begin{align*}
    \text{SU(2)} & \rightarrow \ w^+ w^0 w^- \quad \text{coupling} \quad g \\
    \text{U(1)} & \rightarrow \ b^0 \quad \text{coupling} \quad g'
\end{align*} \]

spontaneous symmetry breaking \( <\phi> = v \)

\[ \begin{align*}
    w^+ w^- & \rightarrow \text{massive} \quad m_W = \frac{g}{2} v \\
    w^0 b^0 & \rightarrow \ z^0 \quad m_Z = \frac{\sqrt{g^2 + g'^2}}{2} v \\
    a^0 & \quad m_A = 0
\end{align*} \]

parity violation

\( w^+ w^- w^0 \) couple only to left-handed quarks and leptons
to complete the story,

A and Z are mixtures of \( W^0 \) and \( B^0 \)

\[
A = \sin \theta_W \ W^0 + \cos \theta_W \ B^0 \\
Z = \cos \theta_W \ W^0 - \sin \theta_W \ B^0
\]

\[
\tan \theta_W = \frac{g'}{g} \quad \sin^2 \theta_W = \frac{g'^2}{g^2 + g'^2}
\]

A couples to \( T^3 + Y = Q \)

\[
e = \frac{g \ g'}{g^2 + g'^2} \quad 2
\]

Z couples to \( \cos^2 \theta_W \ T^3 - \sin^2 \theta_W \ Y \)

\[
Q_Z = ( \ T^3 - \sin^2 \theta_W \ Q )
\]

\( T^3 = \pm \ 1/2 \quad \text{for left-handed q, l} \\
0 \quad \text{for right-handed q, l} \)
In 1989, two new accelerators, LEP at CERN and SLC at SLAC, began operation to study the properties of the $Z^0$ in detail through the reaction $e^+ e^- \rightarrow Z^0$ resonance

the CDF experiment at Fermilab began precise measurement of $m_W$ and showed that the top quark is very heavy ($m_t > m_W$)

This initiated an era of precision electroweak measurements.
so,

what did these experiments measure?

what did we learn?
G. Altarelli, 1989, and 10 years later:
LEP and SLC discovered no new particles and confirmed the Standard Model of electroweak interactions

Some found this a disappointment …

For me, it is an important and beautiful chapter in the progress of physics.
F. Dydak showed this slide already at the 1990 ICHEP:
before we discuss the experiments, I would like to clarify one conceptual issue.

handedness (helicity) is not a Lorentz-invariant concept,

so how can a fundamental interaction be sensitive to it?
Massless particles can have definite helicity.

The most basic representations of the Poincare group are massless L- and R-handed fermions

The truly fundamental interactions see the quarks and leptons at their deepest level, before mass generation

Quark and lepton masses come from spontaneous symmetry breaking:

\[ m_f = \frac{1}{\sqrt{2}} \lambda_f v \]
To test the properties of the $Z^0$, go to high energy where quark and lepton masses are irrelevant.

Separate L and R, and verify:

<table>
<thead>
<tr>
<th></th>
<th>$Q_Z(L)$</th>
<th>$Q_Z(R)$</th>
<th>$S_f$</th>
<th>$A_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu\nu\nu$</td>
<td>$\frac{1}{2}$</td>
<td>$x$</td>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>$e\mu\tau$</td>
<td>$-\frac{1}{2} + \sin^2 \theta_W$</td>
<td>$\sin^2 \theta_W$</td>
<td>0.126</td>
<td>0.15</td>
</tr>
<tr>
<td>$u\nu\tau$</td>
<td>$\frac{1}{2} - \frac{2}{3} \sin^2 \theta_W$</td>
<td>$-\frac{2}{3} \sin^2 \theta_W$</td>
<td>0.144</td>
<td>0.67</td>
</tr>
<tr>
<td>$d\nu\bar{b}$</td>
<td>$-\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W$</td>
<td>$\frac{1}{3} \sin^2 \theta_W$</td>
<td>0.185</td>
<td>0.94</td>
</tr>
</tbody>
</table>

\[
S_f = Q_Z^2(L) + Q_Z^2(R)
\]
\[
A_f = \frac{Q_Z^2(L) - Q_Z^2(R)}{Q_Z^2(L) + Q_Z^2(R)}
\]

a consistent pattern gives a precise values of 
\[
\sin^2 \theta_W
\]
measurement of the $Z^0$ mass:

LEP calibration of $\int ds \, B$ measures the $Z^0$ resonance energy

some final corrections are exotic: tides, level of Lake Geneva, TGV

$$m_Z = 91.1875 (21) \text{ GeV}$$

a new physical constant determined to high precision

reference value of $\sin^2 \theta_W$

$$\sin^2 2\theta_0 = \frac{4\pi\alpha_*}{\sqrt{2}G_F m_Z^2}$$

$$\sin^2 \theta_0 = 0.231079 (36)$$
measurement of $S_f$

$$\Gamma_Z = \frac{\alpha m_Z^2}{6\cos^2\theta_W \sin^2\theta_W} \sum_f Q^2_{Zf} N_f$$

$f$ runs over L and R quarks and leptons

$$N_f = 1 \quad \text{for leptons}$$

$$3 \left( 1 + \frac{\alpha}{\pi} s + \ldots \right) = 3.1 \quad \text{for quarks}$$

Radiation from the initial $e^-$ and $e^+$ substantially distorts the resonance shape

$$\Gamma_Z = 2.4952 (23) \text{ GeV}$$

To determine the $S_f$ separately, count.

SLD 500 K Z s (w. polarized $e^-$)

LEP 17 M Z s (4 experiments)
final $Z$ resonance shape from LEP

- ALEPH
- DELPHI
- L3
- OPAL

measurements, error bars increased by factor 10

from fit

QED unfolded
The SLD detector under construction:
$e^+e^- \rightarrow Z^0 \rightarrow e^+e^-$
$Z^0$ event types, according to ALEPH:

add also $Z \rightarrow \nu \bar{\nu}$ with 3 neutrino species
to determine the $A_f$, we must have a way to determine the spin of the fermion in $Z$ decay

Method 1: angular distribution

$$d\sigma/d\cos\theta = (1 + \cos\theta)^2 \text{ for } e_L^- \rightarrow \mu_L^-$$

$$d\sigma/d\cos\theta = (1 - \cos\theta)^2 \text{ for } e_L^- \rightarrow \mu_R^-$$

polarization average: $(1 + \cos^2\theta)$
Method 2: decay distribution of $\tau$

$\tau_L^-$ → fast $e^-$, fast $\mu^-$, slow $\pi^-$

$\tau_R^-$ → slow $e^-$, slow $\mu^-$, fast $\pi^-$
$e^+ e^- \rightarrow Z^0 \rightarrow \tau^+ \tau^-$
Method 3: Initial state polarization

Make separate $e_L^-$ and $e_R^-$ beams, and measure the asymmetry of

$$\sigma (e_{L,R}^- e^+ \rightarrow Z^0)$$

by counting.

SLD:

$$A_e = 0.1506 (24)$$

$$\sin^2 \theta_W = 0.23097 (27)$$
It is not clear how to do a comparable analysis for quarks:

It is not so obvious how to measure the quark spin, since quarks are seen only as constituents of hadrons.

It is not so obvious how to tell u quarks from d quarks.
$e^+ e^- \rightarrow Z^0 \rightarrow q \bar{q}$
$e^+ e^- \rightarrow Z^0 \rightarrow q \bar{q}$
The axes of these events follow a 
\((1 + \cos^2 \theta)\) distribution.
$e^+ e^- \rightarrow Z^0 \rightarrow q \bar{q} g$
To distinguish species, use the fact that heavy species have definite, measurable, lifetimes:

<table>
<thead>
<tr>
<th></th>
<th>( \tau )</th>
<th>( c_\tau )</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau^- )</td>
<td>0.29 ps</td>
<td>0.09 mm</td>
<td></td>
</tr>
<tr>
<td>( c(D^0) )</td>
<td>0.41 ps</td>
<td>0.12 mm</td>
<td></td>
</tr>
<tr>
<td>( b(B^0) )</td>
<td>1.55 ps</td>
<td>4.6 mm</td>
<td></td>
</tr>
</tbody>
</table>

Even inside a 3-story-high particle detector, there should be a way to measure such distances.
The CCD vertex detector of the SLD: VDX-2
$e^+ e^- \rightarrow Z^0 \rightarrow \tau^+ \tau^-$
$e^+ e^- \rightarrow Z^0 \rightarrow b \bar{b}$
Vertices with a large $c\tau$ should also show a decay to system of large mass

$$(m_D = 1.86 \text{ GeV}, \quad m_B = 5.28 \text{ GeV})$$

Selecting vertices with observed large mass gives a very pure sample of

$$e^+ e^- \rightarrow b \bar{b}$$
Now recall

\[
\frac{d\sigma}{d\cos\theta} ( e^- e^+ \rightarrow b_L \bar{b}_R) \sim (1 + \cos\theta)^2
\]

\[
\frac{d\sigma}{d\cos\theta} ( e^- e^+ \rightarrow b_R \bar{b}_L) \sim (1 - \cos\theta)^2
\]

but also \[ A_b = 0.94 \]

so using a polarized beam (L or R) should have a profound effect on the angular distribution for Z decay to $b \bar{b}$. 
tagged events

L polarization

R polarization

cos thrust

cos thrust
<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
<th>Pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_Z ) [GeV]</td>
<td>( 91.1875 \pm 0.0021 )</td>
<td>.04</td>
</tr>
<tr>
<td>( Z^0 ) [GeV]</td>
<td>( 2.4952 \pm 0.0023 )</td>
<td>-.46</td>
</tr>
<tr>
<td>( \Gamma_{Z} ) [nb]</td>
<td>( 41.540 \pm 0.037 )</td>
<td>1.62</td>
</tr>
<tr>
<td>( R_l )</td>
<td>( 20.767 \pm 0.025 )</td>
<td>1.09</td>
</tr>
<tr>
<td>( A_{fb}^{0,l} )</td>
<td>( 0.01714 \pm 0.00095 )</td>
<td>.79</td>
</tr>
<tr>
<td>( A_{e} )</td>
<td>( 0.1498 \pm 0.0048 )</td>
<td>.41</td>
</tr>
<tr>
<td>( A )</td>
<td>( 0.1439 \pm 0.0041 )</td>
<td>-.96</td>
</tr>
<tr>
<td>( \sin^2 )_{\text{lept \ eff}} )</td>
<td>( 0.2322 \pm 0.0010 )</td>
<td>.78</td>
</tr>
<tr>
<td>( m_W ) [GeV]</td>
<td>( 80.446 \pm 0.040 )</td>
<td>1.32</td>
</tr>
<tr>
<td>( R_b )</td>
<td>( 0.21664 \pm 0.00068 )</td>
<td>1.32</td>
</tr>
<tr>
<td>( R_c )</td>
<td>( 0.1729 \pm 0.0032 )</td>
<td>.20</td>
</tr>
<tr>
<td>( A_{fb}^{0,b} )</td>
<td>( 0.0982 \pm 0.0017 )</td>
<td>-3.20</td>
</tr>
<tr>
<td>( A_{fb}^{0,c} )</td>
<td>( 0.0689 \pm 0.0035 )</td>
<td>-1.48</td>
</tr>
<tr>
<td>( A_b )</td>
<td>( 0.921 \pm 0.020 )</td>
<td>-.68</td>
</tr>
<tr>
<td>( A_c )</td>
<td>( 0.667 \pm 0.026 )</td>
<td>-.05</td>
</tr>
<tr>
<td>( A_l )</td>
<td>( 0.1513 \pm 0.0021 )</td>
<td>1.68</td>
</tr>
<tr>
<td>( \sin^2 )_{\text{W}} )</td>
<td>( 0.2255 \pm 0.0021 )</td>
<td>1.20</td>
</tr>
<tr>
<td>( m_W ) [GeV]</td>
<td>( 80.452 \pm 0.062 )</td>
<td>.95</td>
</tr>
<tr>
<td>( m_t ) [GeV]</td>
<td>( 174.3 \pm 5.1 )</td>
<td>-.27</td>
</tr>
<tr>
<td>( \frac{\Gamma}{\Gamma_{\text{had}}}(m_Z) )</td>
<td>( 0.02761 \pm 0.00036 )</td>
<td>-.36</td>
</tr>
</tbody>
</table>

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LEP Electroweak Working Group
A recent contribution:

measurements by the four LEP experiments of $e^+ e^-$ cross sections up to 200 GeV.

At asymptotic energies, where spontaneous symmetry breaking can be neglected:

$$\sigma \sim | \cos^2 \theta_W T_e^3 T_f^3 + \sin^2 \theta_W Y_e Y_f |^2$$

At 200 GeV, we already come very close to this state.
DELPHI

Cross Section (nb)

Energy (GeV)

hadrons
muons
taus

$s' > 0.10 \div s$
$s' > 0.85 \div s$
$s' > 75 \text{ GeV} (x 0.1)$
$s' > 0.85 \div s (x 0.1)$
data compilation by M. Hildreth
In all, a large number of observables are in excellent agreement with the predictions of the Standard Model.

The level of agreement requires taking account of order $\alpha$ electroweak radiative corrections:
What have we learned?

1. Quarks and leptons are real!
   We can directly manipulate their scattering and spin

2. The nature of weak interactions is a solved problem.
   It is time to move on to the next deeper level.
3. We have some clues to the nature of physics at the next level.

The precision electroweak measurements are sensitive to any new physics that couples to the weak interactions.

- new heavy quarks and leptons
- Higgs bosons
- ....

Theories in which these contributions to electroweak corrections do not cancel are excluded!

Method of analysis:
- parametrize vacuum polarization diagrams by 2 parameters (S, T),
- look for a consistent determination
S,T fits from 1990, 1998:
The current $S, T$ fit is in good agreement with

- a top quark with the observed mass,
  \[ m_t = 173 \pm 5 \ \text{GeV} \]
- a Higgs boson which must be light,
  \[ m_h < 170 \ \text{GeV} \]
- additional new physics, only if it gives very small electroweak corrections
A light Higgs boson, a heavy top quark, small electroweak corrections, are all predictions of supersymmetry.

The new precise determination of the coupling constants $g$, $g'$, and $g_s$ give another hint for this theory;

extrapolate to short distances, noting that pair creation and other quantum effects modify the values of these coupling constants as a function of distance scale.
Standard Model with superpartners
Today, we have only hints about physics at very small scales, but the success of the precision study of electroweak interactions gives the promise that we will be able to find out exactly what is hiding there.