From LEP to LHC

1. Physics of the Z boson (I)
2. Physics of the Z boson (II)
3. Physics of the W boson
4. Physics of the top quark
5. Tests of the Standard Model
6. Search for the Higgs boson (I)
7. Search for the Higgs boson (II)

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1. Physics of the Z boson (I)
   • LEP (Statistics interlude)

2. Physics of the Z boson (II)
   • LEP (Statistics interlude)

3. Physics of the W boson
   • LEP, Tevatron, LHC (Statistics interlude)

4. Physics of the top quark
   • Tevatron, LHC

5. Tests of the Standard Model
   • LEP, Tevatron

6. Search for the Higgs boson (I)
   • LEP (Statistics interlude)

7. Search for the Higgs boson (II)
   • Tevatron, LHC

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(Salvatore.Mele@cern.ch)
Tests of the Standard Model

- Couplings and parameters
- The asymmetry parameters, reloaded
- Measurements of the strong coupling
- Measurements of the electromagnetic coupling
- The Standard Model “black box”
- Measurements and predictions
- Alternative point of views
Some bibliographic references

arXiv:0712.0929
Nuts and bolts of the Standard Model

At tree level electromagnetic and weak couplings are related as:

\[ G_F = \frac{\pi \alpha}{\sqrt{2} m_W^2 \sin^2 \theta_W^{\text{tree}}} \]

The neutral- and charged-current sectors are related as:

\[ \rho_0 = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W^{\text{tree}}} \]

In a model with only one Higgs-boson doublet

\[ \rho_0 = 1 \]
Tree-level L and R fermion couplings

\[
g_L^{\text{tree}} = \sqrt{\rho_0} \left( T_3^f - Q_f \sin^2 \theta_W^{\text{tree}} \right) \\
g_R^{\text{tree}} = -\sqrt{\rho_0} Q_f \sin^2 \theta_W^{\text{tree}},
\]

<table>
<thead>
<tr>
<th>Family</th>
<th>( T )</th>
<th>( T_3 )</th>
<th>( Q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \begin{pmatrix} \nu_e \ e \end{pmatrix} ) _L, ( \begin{pmatrix} \nu_\mu \ \mu \end{pmatrix} ) _L, ( \begin{pmatrix} \nu_\tau \ \tau \end{pmatrix} ) _L</td>
<td>1/2</td>
<td>+1/2</td>
<td>0</td>
</tr>
<tr>
<td>( \nu_{eR} ), ( \nu_{\mu R} ), ( \nu_{\tau R} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( e_R ), ( \mu_R ), ( \tau_R )</td>
<td>0</td>
<td>0</td>
<td>-1</td>
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<tr>
<td>( \begin{pmatrix} u \ d \end{pmatrix} ) _L, ( \begin{pmatrix} c \ s \end{pmatrix} ) _L, ( \begin{pmatrix} t \ b \end{pmatrix} ) _L</td>
<td>1/2</td>
<td>+1/2</td>
<td>+2/3</td>
</tr>
<tr>
<td>( u_R ), ( c_R ), ( t_R )</td>
<td>0</td>
<td>0</td>
<td>+2/3</td>
</tr>
<tr>
<td>( d_R ), ( s_R ), ( b_R )</td>
<td>0</td>
<td>0</td>
<td>-1/3</td>
</tr>
</tbody>
</table>
Tree-level V and A fermion couplings

\[
\begin{align*}
    g_V^{\text{tree}} & \equiv g_L^{\text{tree}} + g_R^{\text{tree}} = \sqrt{\rho_0} \left( T_3^f - 2Q_f \sin^2 \theta_W^{\text{tree}} \right) \\
    g_A^{\text{tree}} & \equiv g_L^{\text{tree}} - g_R^{\text{tree}} = \sqrt{\rho_0} T_3^f.
\end{align*}
\]

<table>
<thead>
<tr>
<th>Family</th>
<th>( T )</th>
<th>( T_3 )</th>
<th>( Q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>\begin{pmatrix} \nu_e \ e \end{pmatrix}<em>L, \begin{pmatrix} \nu</em>\mu \ \mu \end{pmatrix}<em>L, \begin{pmatrix} \nu</em>\tau \ \tau \end{pmatrix}<em>L, \nu</em>{eR}, \nu_{\mu R}, \nu_{\tau R}, e_R, \mu_R, \tau_R</td>
<td>1/2</td>
<td>+1/2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-1/2</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>\begin{pmatrix} u \ d \end{pmatrix}_L, \begin{pmatrix} c \ s \end{pmatrix}_L, \begin{pmatrix} t \ b \end{pmatrix}_L, u_R, c_R, t_R, d_R, s_R, b_R</td>
<td>1/2</td>
<td>+1/2</td>
<td>+2/3</td>
</tr>
<tr>
<td></td>
<td>-1/2</td>
<td>-1/3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>+2/3</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>-1/3</td>
</tr>
</tbody>
</table>
Life is not at tree-level

Electroweak corrections to the propagators

These are actually a good thing!
(Higgsometry, more later)
Life is not at tree-level
“Effective” quantities

Define the electroweak mixing angle including all electroweak corrections as:

$$\rho_0 = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} = 1$$

Absorbing the electroweak corrections into two form factors the “effective” couplings are:

$$\sin^2 \theta^f_{\text{eff}} \equiv \kappa_f \sin^2 \theta_W$$
$$g_{Vf} \equiv \sqrt{\rho_f} \left( T^f_3 - 2 Q_f \sin^2 \theta^f_{\text{eff}} \right)$$
$$g_{Af} \equiv \sqrt{\rho_f} T^f_3 ,$$
“Effective” quantities

Define \( \sin^2 \theta_{\text{eff}}^f \equiv \kappa_f \sin^2 \theta_W \) to keep the same structures for the basic formulas

\[
\begin{align*}
\rho_0 &= \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \\
g_V^{\text{tree}} &= \sqrt{\rho_0} \left( T_3^f - 2Q_f \sin^2 \theta_W^{\text{tree}} \right) \\
g_A^{\text{tree}} &= \sqrt{\rho_0} T_3^f.
\end{align*}
\]

\[
\begin{align*}
\rho_0 &= \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \\
g_V^f &= \sqrt{\rho} \left( T_3^f - 2Q_f \sin^2 \theta_{\text{eff}}^f \right) \\
g_A^f &= \sqrt{\rho} T_3^f.
\end{align*}
\]
Measuring $\sin^2 \theta_{\text{eff}}^f$ from $g_{Vf}$ and $g_{Af}$

$$\frac{g_{Vf}}{g_{Af}} = 1 - \frac{2Q_f}{T_3^f} \sin^2 \theta_{\text{eff}}^f = 1 - 4|Q_f| \sin^2 \theta_{\text{eff}}^f$$

g_{Vf}$ and $g_{Af}$ measured via the asymmetry parameters $A_f$

$$A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2} = \frac{2g_{Vf}g_{Af}}{g_{Vf}^2 + g_{Af}^2} = 2 \frac{g_{Vf}/g_{Af}}{1 + (g_{Vf}/g_{Af})^2}$$

Concentrate on $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ for which the sensitivity is high
The $A_f$ parameters

\[ A_{FB}^{0,1} = \frac{3}{4} A_e A_1 \]
\[ A_{FB}^{0,b} = \frac{3}{4} A_e A_b \]
\[ A_{LR} = A_e \]
\[ A_{LRFB} = \frac{3}{4} A_f \]
\[ P_\tau = f(A_e, A_\tau) \]

Measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$A_{FB}^{0,\ell}$</th>
<th>$A_{LR}, A_{LRFB}^{\ell}$</th>
<th>$P_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_e$</td>
<td>0.139±0.012</td>
<td>0.1516±0.0021</td>
<td>0.1498±0.0049</td>
</tr>
<tr>
<td>$A_\mu$</td>
<td>0.162±0.019</td>
<td>0.142±0.015</td>
<td>—</td>
</tr>
<tr>
<td>$A_\tau$</td>
<td>0.180±0.023</td>
<td>0.136±0.015</td>
<td>0.1439±0.0043</td>
</tr>
</tbody>
</table>

Combinations ($\chi^2 = 3.6/5$)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Correlations $A_e$, $A_\mu$, $A_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_e$</td>
<td>0.1514±0.0019</td>
<td>1.00</td>
</tr>
<tr>
<td>$A_\mu$</td>
<td>0.1456±0.0091</td>
<td>−0.10 1.00</td>
</tr>
<tr>
<td>$A_\tau$</td>
<td>0.1449±0.0040</td>
<td>−0.02 0.01 1.00</td>
</tr>
</tbody>
</table>

Leptonic universality

$A_\ell = 0.1501 ± 0.0016$
The $A_f$ parameters

Measurements from heavy quarks

\[
A_{FB}^{0,1} = \frac{3}{4} A_e A_l
\]

\[
A_{FB}^{0,b} = \frac{3}{4} A_e A_b
\]

\[
A_{LR}^0 = A_e
\]

\[
A_{LRFB}^0 = \frac{3}{4} A_f
\]

\[
P_T = f(A_e, A_\tau)
\]

Combinations from leptons

<table>
<thead>
<tr>
<th>Flavour $q$</th>
<th>$A_q = \frac{4}{3} \frac{A_{FB}^{0,q}}{A_e}$</th>
<th>Direct $A_q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>0.881±0.017</td>
<td>0.923±0.020</td>
</tr>
<tr>
<td>c</td>
<td>0.628±0.032</td>
<td>0.670±0.027</td>
</tr>
</tbody>
</table>

Results of all the above

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_\ell$</td>
<td>0.1489±0.0015</td>
<td>1.00</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.899±0.013</td>
<td>-0.42 1.00</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.654±0.021</td>
<td>-0.10 0.15 1.00</td>
</tr>
</tbody>
</table>
Compare $A_f$ from different measurements

$$A^0_{LRFB} = \frac{3}{4} A_f$$

$\chi^2$/dof = 4.5/4
34%

$$A^0_{FB} = \frac{3}{4} A_e A_f$$

$$A^0_{LRFB} = \frac{3}{4} A_l$$

$$A^0_{FB} = \frac{3}{4} A_e A_l$$

$$P_\tau = f(A_e, A_\tau)$$
Extract $g_{Af}$ & $g_{Vf}$ from asymmetry parameters $A_f$

$$A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2} = \frac{2g_{Vf}g_{Af}}{g_{Vf}^2 + g_{Af}^2} = 2 \frac{g_{Vf}/g_{Af}}{1 + (g_{Vf}/g_{Af})^2}$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>$g_{A\nu}$</th>
<th>$g_{Ae}$</th>
<th>$g_{A\mu}$</th>
<th>$g_{A\tau}$</th>
<th>$g_{V\nu}$</th>
<th>$g_{V\mu}$</th>
<th>$g_{V\tau}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{A\nu} \equiv g_{V\nu}$</td>
<td>$+0.5003\pm0.0012$</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$g_{Ae}$</td>
<td>$-0.50111\pm0.00035$</td>
<td>$-0.75$</td>
<td>1.00</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$g_{A\mu}$</td>
<td>$-0.50120\pm0.00054$</td>
<td>0.39</td>
<td>$-0.13$</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$g_{A\tau}$</td>
<td>$-0.50204\pm0.00064$</td>
<td>0.37</td>
<td>$-0.12$</td>
<td>0.35</td>
<td>1.00</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$g_{V\nu}$</td>
<td>$-0.03816\pm0.00047$</td>
<td>$-0.10$</td>
<td>0.01</td>
<td>$-0.01$</td>
<td>$-0.03$</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$g_{V\mu}$</td>
<td>$-0.0367\pm0.0023$</td>
<td>0.02</td>
<td>0.00</td>
<td>$-0.30$</td>
<td>0.01</td>
<td>$-0.10$</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>$g_{V\tau}$</td>
<td>$-0.0366\pm0.0010$</td>
<td>0.02</td>
<td>$-0.01$</td>
<td>0.01</td>
<td>$-0.07$</td>
<td>$-0.02$</td>
<td>0.01</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Measurements of $\sin^2\theta_{\text{lept}}^{\text{eff}}$

The values extracted from $A_{LR}$ and $A_{FB}^b$ are the most precise and differ by $3.2\sigma$

$$\frac{0.23220}{\sqrt{0.00026^2 + 0.00029^2}} = 3.2$$
Time evolution of the $A_{LR}/A_{FB}^b$ discrepancy
Statistical interlude: what’s a “sigma”? 

\[ f(x; \mu, \sigma) \]

\[
\begin{array}{c|c|c|c|c|c}
\alpha & \delta & \alpha & \delta \\
0.3173 & 1\sigma & 0.2 & 1.28\sigma \\
4.55 \times 10^{-2} & 2\sigma & 0.1 & 1.64\sigma \\
2.7 \times 10^{-3} & 3\sigma & 0.05 & 1.96\sigma \\
6.3 \times 10^{-5} & 4\sigma & 0.01 & 2.58\sigma \\
5.7 \times 10^{-7} & 5\sigma & 0.001 & 3.29\sigma \\
2.0 \times 10^{-9} & 6\sigma & 10^{-4} & 3.89\sigma \\
\end{array}
\]
From the experimental point of view, no systematic effect potentially explaining such shifts in the measurement of $A_{FB}^{0,b}$ has been identified. While the QCD corrections are significant, their uncertainties are small compared to the total errors and are taken into account.

All known uncertainties are investigated and are taken into account in the analyses. The same holds for the $A_{LR}^{0}$ measurement, where the most important source of systematic uncertainty, namely the determination of the beam polarization, is small and well-controlled.

Thus the shift is either a sign for new physics which invalidates the simple relations between the effective parameters assumed in this chapter, or a fluctuation in one or more of the input measurements. In the following we assume that measurement fluctuations are responsible.
Parameters of the Standard Model

• Three couplings for three forces
  Electromagnetic: $\alpha$, weak: $G_F$, strong: $\alpha_S$
  The relation $G_F = \frac{\pi \alpha}{\sqrt{2} m_W^2 \sin^2 \theta_W^{\text{tree}}}$ reduces them to two: $\alpha$ and $\alpha_S$
  $G_F$ is measured: $(1.166371 \pm 0.000006) \times 10^{-5}$ (MuLan)
  $G_F$ is measured: $(1.166353 \pm 0.000009) \times 10^{-5}$ (FAST)

• Fermion masses
  All light quarks are not relevant at these energies: $m_t$

• Boson masses
  The photon is massless
  Given $G_F = \frac{\pi \alpha}{\sqrt{2} m_W^2 \sin^2 \theta_W^{\text{tree}}}$ use $G_F$ instead of $m_W$
  It reduces to $m_Z$

• And of course... the Higgs-boson mass $m_H$
The electromagnetic coupling (constant)

The fine-structure constant is a fundamental quantity of Physics, measured with high precision

\[ 1/\alpha_0 = 137.03599911 \pm 0.00000046 \]
CODATA, Rev.Mod.Phys 72(2000)351

In quantum field theory, owing to vacuum polarisation, the electromagnetic coupling runs with the squared momentum transfer

\[ \alpha(Q^2) = \frac{\alpha_0}{1 - \Delta\alpha(Q^2)} \]

where for \( m_f < m_W, Q^2 \)

\[ \Delta\alpha(Q^2) = \frac{\alpha_0}{3\pi} \sum_f q_f^2 (N_c)_f \left( \ln \frac{Q^2}{m_f^2} - \frac{5}{3} \right) + ... \]

\[ \Delta\alpha(Q^2) = \Delta\alpha_{\text{leptons}}(Q^2) + \Delta\alpha_{\text{hadrons}}(Q^2) \]

- \( \Delta\alpha_{\text{leptons}}(Q^2) \) is nicely computed
- \( \Delta\alpha_{\text{hadrons}}(Q^2) \) to be derived from data+theory (with uncertainty)
Describing the running of $\alpha$

\[
\alpha(Q^2) = \frac{\alpha_0}{1 - \Delta \alpha(Q^2)} = \frac{\alpha_0}{1 - \Delta \alpha_{\mu\tau}(Q^2) - \Delta \alpha_{\text{top}}(Q^2) - \Delta \alpha_{\text{had}}^{(5)}(Q^2)}
\]

\[
\Delta \alpha_{\mu\tau}(m_Z^2) = 0.03150
\]

Steinhauser, PLB 429(1998)158

\[
\Delta \alpha_{\text{top}}(m_Z^2) = -0.00007 \pm 0.00001
\]

Montagna, CPC 117 (1999)278
Arbuzov, hep-ph/0507146

\[
\Delta \alpha_{\text{had}}^{(5)}(m_Z^2) = 0.02758 \pm 0.00035
\]

Burkhardt&Pietrzyk, PRD 72(2005)057501

\[
\frac{1}{\alpha(m_Z^2)} = 128.940 \pm 0.048
\]
Describing the running of $\alpha$

The hadronic contribution is derived as

$$\Delta \alpha^{(5)}_{\text{had}}(Q^2) = -\frac{\alpha Q^2}{3\pi} \Re \int_{4m_e^2}^{\infty} ds \frac{R_{\text{had}}(s)}{s(s-Q^2-i\varepsilon)}$$

from the hadronic cross section

$$R_{\text{had}} = \frac{\sigma(e^+e^-\rightarrow \text{hadrons})}{\sigma(e^+e^-\rightarrow \mu^+\mu^-)}$$

which results into:

$$\Delta \alpha^{(5)}_{\text{had}}(m_Z^2) = 0.02758 \pm 0.00035$$

$$\frac{1}{\alpha(m_Z^2)} = 128.940 \pm 0.048$$
The strong coupling (constant)

Identify processes which are experimentally and theoretically “clean” to study in order to extract $\alpha_S$

- **Measurement from the branching ratio of tau leptons**

\[
R_\tau = \frac{B(\tau \to h \nu_\tau)}{B(\tau \to e\bar{\nu}_e \nu_\tau)} = \frac{1 - B(\tau \to e\bar{\nu}_e \nu_\tau) - B(\tau \to \mu\bar{\nu}_\mu \nu_\tau)}{B(\tau \to e\bar{\nu}_e \nu_\tau)} \\
= 3 \, (|V_{ud}|^2 + |V_{us}|^2) \, S_{EW} \\
\times \left( 1 + \frac{\alpha_s}{\pi} + 5.2023 \left( \frac{\alpha_s}{\pi} \right)^2 + 26.366 \left( \frac{\alpha_s}{\pi} \right)^3 + (78 + d_3) \left( \frac{\alpha_s}{\pi} \right)^4 + \delta_{NP} \right)
\]

- **Measurement from the jet rates at LEP**

- **Measurement from the event shapes at LEP**
Fraction of n jet events at LEP

N-jet Fraction = Number of events with 2, 3, 4 or 5 jets / Number of events with jets

Remember, $y_{\text{cut}}$ is the cut of the threshold to aggregate “particles” into “jetlets” in the JADE algorithm, with distance:

$$y_{ij} = 2 \frac{E_i E_j (1-\cos \theta_{ij})}{E_{\text{vis}}^2}$$
Event-shape variables

Sensitive to the number and kinematics of jets, and therefore to $\alpha_s$.

Example: Trust. Fit 5 different variables at 9 energy points.

\[ T = \frac{\sum |\vec{p}_i \cdot \hat{n}_T|}{\sum |\vec{p}_i|} \]
Event shape variables, the whole enchillada

G. Dissertori et al arXiv:07120327
Knowledge of theoretical shapes to fit is (was?) a limiting factor
A world average of $\alpha_S$

S. Bethke arXiv:hep-ex/0407021
Radiative corrections

Electroweak processes “feel” bosons and fermions
The Standard Model black-box

Use input parameters...

to predict values...

to compare to measurements...

...to check the Standard Model
...to predict $m_H$

$\alpha$
$\alpha_S$
$m_Z$
$m_t$
$m_H$

$G_F$

$\chi^2$ fit

$m_Z \Gamma_Z \sigma_{\text{had}} R_l A_{\text{FB}} A_{\text{LR}}$

$m_W$
$m_t$

Salvatore Mele | From LEP to LHC | Troisième cycle
Impressive evidence for EW effects in radiative corrections
Some Standard Model predictions
Another Standard Model prediction

The top is “easy” to “discover” at LEP: radiative corrections depend on $m_t^2$!

Unfortunately they only only depend on $\log_{10} m_H$!
The measured values of $m_W$ and $m_t$
The health chart of the Standard Model

1. Chose one parameter
2. Remove it from the fit
3. Predict its value from all other contributions
4. Compare to data

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>( \frac{O_{\text{fit}} - O_{\text{meas}}}{\sigma_{\text{meas}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \alpha_{\text{had}}^{(5)}(m_Z) )</td>
<td>0.02758 ± 0.00035</td>
<td>0.02767</td>
</tr>
<tr>
<td>( m_Z ) [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>91.1875</td>
</tr>
<tr>
<td>( \Gamma_Z ) [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>2.4958</td>
</tr>
<tr>
<td>( \sigma_{\text{had}}^0 ) [nb]</td>
<td>41.540 ± 0.037</td>
<td>41.478</td>
</tr>
<tr>
<td>( R_l )</td>
<td>20.767 ± 0.025</td>
<td>20.743</td>
</tr>
<tr>
<td>( A_{\text{fb}}^{0,\perp} )</td>
<td>0.01714 ± 0.00095</td>
<td>0.01644</td>
</tr>
<tr>
<td>( A_l(P_Z) )</td>
<td>0.1465 ± 0.0032</td>
<td>0.1481</td>
</tr>
<tr>
<td>( R_b )</td>
<td>0.21629 ± 0.00066</td>
<td>0.21582</td>
</tr>
<tr>
<td>( R_c )</td>
<td>0.1721 ± 0.0030</td>
<td>0.1722</td>
</tr>
<tr>
<td>( A_{\text{fb}}^{0,b} )</td>
<td>0.0992 ± 0.0016</td>
<td>0.1038</td>
</tr>
<tr>
<td>( A_{\text{fb}}^{0,c} )</td>
<td>0.0707 ± 0.0035</td>
<td>0.0742</td>
</tr>
<tr>
<td>( A_b )</td>
<td>0.923 ± 0.020</td>
<td>0.935</td>
</tr>
<tr>
<td>( A_c )</td>
<td>0.670 ± 0.027</td>
<td>0.668</td>
</tr>
<tr>
<td>( A_l ) (SLD)</td>
<td>0.1513 ± 0.0021</td>
<td>0.1481</td>
</tr>
<tr>
<td>( \sin^2 \theta_{\text{eff}}(Q_{\text{ib}}) )</td>
<td>0.2324 ± 0.0012</td>
<td>0.2314</td>
</tr>
<tr>
<td>( m_W ) [GeV]</td>
<td>80.399 ± 0.025</td>
<td>80.376</td>
</tr>
<tr>
<td>( \Gamma_W ) [GeV]</td>
<td>2.098 ± 0.048</td>
<td>2.092</td>
</tr>
<tr>
<td>( m_t ) [GeV]</td>
<td>172.4 ± 1.2</td>
<td>172.5</td>
</tr>
</tbody>
</table>
Measured vs. predicted: $m_W$ and $m_t$

W-Boson Mass [GeV]
- TEVATRON: $80.432 \pm 0.039$
- LEP2: $80.376 \pm 0.033$
- Average: $80.399 \pm 0.025$

Top-Quark Mass [GeV]
- CDF: $172.1 \pm 1.6$
- DØ: $172.7 \pm 1.6$
- Average: $172.4 \pm 1.2$

Repeat the fit leaving $m_W$ or $m_t$ as a free parameter
Measured vs. predicted: $m_W$ and $m_t$

Repeat the fit leaving $m_W$ or $m_t$ as a free parameter.
Measured vs. predicted: $m_W$ and $m_t$

Repeat the fit leaving $m_W$ and $m_t$ as a free parameters.
Limitology

\[ m_H < 154 \text{ GeV} \text{ @ } 95\% \text{ C.L.} \quad \text{With blue band included} \]

\[ m_H > 114.4 \text{ GeV} \text{ @ } 95\% \text{ C.L.} \quad \text{LEP-I direct search} \]

\[ m_H < 185 \text{ GeV} \text{ @ } 95\% \text{ C.L.} \quad \text{Combination of the above} \]
Breakdown of the sensitivities to $m_H$

Fit $m_H$ from 5 parameters

4 parameters $\rightarrow$

5th parameter $\rightarrow$

The discrepancies between $A_{LR}$ and $A^b_{FB}$ are important when it comes to predict the Higgs mass.

Need to push $m_W$ measurement.

\[
\Delta \alpha_{\text{had}}^{(5)}(m_W^2) = 0.02758 \pm 0.00035, \quad \alpha_S(m_W^2) = 0.118 \pm 0.003, \quad m_Z = 91.1875 \pm 0.0021 \text{ GeV} \quad m_t = 172.4 \pm 1.2 \text{ GeV}
\]
Constraints on $m_H$ from $A_{LR}$ $A_{FB}^b$ and $m_W$

$A_{fb}^{0,l}$
$A_{fb}^{l}(P_z)$
$A_{fb}(SLD)$

Average $0.23153 \pm 0.00016$

$\chi^2$/d.o.f.: 11.8/5

$\Delta \alpha^{(5)}_{\text{had}} = 0.02758 \pm 0.00035$
linearly added to

$M_t = 171.4 \pm 2.1$ GeV

$\Delta \alpha_{\text{lep}} = 0.02758 \pm 0.00035$

$\sin^2 \theta_{\text{eff}}^{\text{lept}}$

$10^3$

$10^2$

$0.232$

$0.233$

$0.234$

$0.235$

$0.236$

$0.237$

$0.238$

$80.2$

$80.3$

$80.4$

$80.5$

$80.6$
## How healthy is the Standard Model?

<table>
<thead>
<tr>
<th></th>
<th>all Z-pole data</th>
<th>all Z-pole data plus $m_t$</th>
<th>all Z-pole data plus $m_W$, $\Gamma_W$</th>
<th>all Z-pole data plus $m_t$, $m_W$, $\Gamma_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_t$ [GeV]</td>
<td>173$^{+13}_{-10}$</td>
<td>172.4$^{+1.2}_{-1.2}$</td>
<td>179$^{+12}_{-9}$</td>
<td>172.5$^{+1.2}_{-1.2}$</td>
</tr>
<tr>
<td>$m_H$ [GeV]</td>
<td>111$^{+190}_{-60}$</td>
<td>110$^{+55}_{-38}$</td>
<td>144$^{+240}_{-81}$</td>
<td>84$^{+34}_{-26}$</td>
</tr>
<tr>
<td>$\log_{10}(m_H/\text{GeV})$</td>
<td>2.05$^{+0.43}_{-0.34}$</td>
<td>2.04$^{+0.18}_{-0.19}$</td>
<td>2.16$^{+0.42}_{-0.35}$</td>
<td>1.93$^{+0.15}_{-0.16}$</td>
</tr>
<tr>
<td>$\alpha_s(m_Z^2)$</td>
<td>0.1190 ± 0.0027</td>
<td>0.1190 ± 0.0027</td>
<td>0.1190 ± 0.0028</td>
<td>0.1185 ± 0.0026</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f. ($P$)</td>
<td>16.0/10 (9.9%)</td>
<td>16.0/11 (14%)</td>
<td>16.8/12 (16%)</td>
<td>17.3/13 (18%)</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}}$</td>
<td>0.23149 ± 0.00016</td>
<td>0.23149 ± 0.00016</td>
<td>0.23143 ± 0.00014</td>
<td>0.23139 ± 0.00013</td>
</tr>
<tr>
<td>$\sin^2 \theta_W$</td>
<td>0.22331 ± 0.00062</td>
<td>0.22332 ± 0.00039</td>
<td>0.22289 ± 0.00038</td>
<td>0.22306 ± 0.00029</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.363 ± 0.032</td>
<td>80.363 ± 0.020</td>
<td>80.385 ± 0.020</td>
<td>80.376 ± 0.015</td>
</tr>
</tbody>
</table>
Statistical Interlude

![Chi-squared distribution plot]

- p-value for test
- α for confidence intervals
- n = 1, 2, 3, 4, 6, 8, 15, 25, 40
- 16.0/10
- 16.0/11
- 16.8/12
- 17.3/13
Statistical Interlude

\[
\chi^2/n
\]

Degrees of freedom $n$

- $16.0/10 = 1.60$
- $16.0/11 = 1.45$
- $16.8/12 = 1.40$
- $17.3/13 = 1.33$

Salvatore Mele | From LEP to LHC | Troisième cycle 46
Remember...

Nice $\chi^2$ values are obtained after having combined most of the measurements.

\[
\begin{align*}
\chi^2_{data,WA} &= \sum_{i=1}^{N} \frac{(Q_i - \bar{Q})^2}{\sigma_i^2} & &\text{1. Are separate data consistent?}
\chi^2_{data,Thy} &= \sum_{i=1}^{N} \frac{(Q_i - Q_{Thy})^2}{\sigma_i^2} & &\text{2. Do all data agree with theory?}
\chi^2_{WA,Thy} &= \frac{(\bar{Q} - Q_{Thy})^2}{\bar{\sigma}^2} & &\text{3. Do averages agree with theory?}
\end{align*}
\]

For uncorrelated Gaussian-distributed uncertainties it holds

\[
\chi^2_{data,Thy} = \chi^2_{data,WA} + \chi^2_{WA,Thy}
\]

So far we looked at 1 for the single observables and at 2 for the SM overall fit.

the answer to 3 might be VERY different

Measuring $\sin^2 \theta_W$ in neutrino scattering

Measure ratio of neutral and charge current events

$$R^- = \frac{\sigma_{NC}^\nu - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^\nu - \sigma_{CC}^{\bar{\nu}}} = \rho^2 \left( \frac{1}{2} - \sin^2 \theta_W \right)$$

Use Fermilab neutrino and antineutrino beam
NuTeV measurement

$\sin^2\theta_W = 0.2277 \pm 0.0013 \pm 0.0009$

Standard Model Fit $\sin^2\theta_W = 0.22335 \pm 0.00062$

The two values are $3\sigma$ away

(There might be some QCD and nuclear effects in the way)
Another way of looking at NuTeV
Changing fit technique and including the Higgs limits

HJ. Flacher et al arXiv:08110009
Conclusions

...even though there are two puzzles:

$A_{LR}$ vs $A_{FB}^b$ and nuTeV vs high-$Q^2$

and alternative points of view give different ideas on overall agreement: need to find the Higgs!