VIII. Experimental tests of the Standard Model

1. Discovery of W and Z boson
2. Precision tests of the Z sector
3. Precision test of the W sector
4. Radiative corrections and prediction of the Higgs mass
5. Higgs searches at the LHC

1. Discovery of the W and Z boson

1983 at CERN SppS accelerator, \( \sqrt{s} \approx 540 \) GeV, UA-1/2 experiments

1.1 Boson production in pp interactions

\[
p \rightarrow W \rightarrow \ell^+ \ell^- + X
\]

\[
p \rightarrow Z \rightarrow \ell^+ \ell^- + X
\]

Similar to Drell-Yan: (photon instead of W)

\[\hat{s} = x_q x_s \hat{s} \text{ mit } \langle x_q \rangle \approx 0.12\]

\[\hat{s} = \left(\frac{x_q}{x_s}\right)^2 \hat{s} \approx 0.014 \hat{s} = (65 \text{ GeV})^2\]

\rightarrow Cross section is small!
1.2 UA-1 Detector

1.3 Event signature: \( p\bar{p} \rightarrow Z \rightarrow \ell^+\ell^- + X \)

High-energy lepton pair:
\[
m^2_{\ell\ell} = (p_{\ell^+} + p_{\ell^-})^2 = M_Z^2
\]

\( M_Z \approx 91 \text{ GeV} \)
1.4 Event signature: $p\bar{p} \rightarrow W \rightarrow \ell \bar{\nu} + X$

**Undetected $\nu$:**
- Missing momentum

**High-energy lepton:**
- Large transverse momentum $p_T$

How can the W mass be reconstructed?

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**W mass measurement**

In the **W rest frame**:
- $|\vec{p}^*| = |\bar{\nu}| = \frac{M_W}{2}$
- $|p_T^*| \leq \frac{M_W}{2}$

In the **lab system**:
- W system boosted only along z axis
- $p_T$ distribution is conserved

**Jacobian Peak:**

$$\frac{dN}{dp_T} = \frac{2p_T}{M_W} \left( \frac{M_W^2}{4} - p_T^2 \right)^{-1/2}$$

- Trans. Movement of the W
- Finite W decay width
- W decay not isotrop

$M_W \approx 80$ GeV
The Nobel Prize in Physics 1984

Carlo Rubbia
Simon van der Meer

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

One of the achievements to allow high-intensity p⁻ p collisions, is stochastic cooling of the p beams before inserting them into SPS.

1.5 Production of Z and W bosons in e⁺e⁻ annihilation

Precision tests of the Z sector

Tests of the W sector
2. Precision tests of the Z sector (LEP and SLC)

2.1 Cross section for $e^+ e^- \rightarrow \gamma/Z \rightarrow f\bar{f}$

$$|M|^2 = \begin{vmatrix} \gamma \\ Z \end{vmatrix} \begin{vmatrix} \gamma \\ Z \end{vmatrix}^2$$

for $e^+ e^- \rightarrow \mu^+ \mu^-$

$$M_\gamma = - e^2 (\bar{\mu} \gamma_\mu \mu) \frac{1}{q^2} (\bar{e} \gamma^\nu e)$$

$$M_Z = - g^2 \frac{1}{\cos^2 \theta_w} \left[ \bar{\gamma} \gamma + \frac{1}{2} (g_{\nu\gamma}^\nu - g_{\nu\gamma}^\nu)^e \right]$$

Z propagator considering a finite Z width

One finds for the differential cross section:

$$\frac{d\sigma}{d\cos \theta} = \frac{\pi \alpha^2}{2s} \left[ F_\gamma (\cos \theta) + F_{\gamma Z} (\cos \theta) \frac{s(s - M_Z^2)}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} + F_Z (\cos \theta) \frac{s^2}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \right]$$

Vanishes at $\sqrt{s} = M_Z$

$$F_\gamma (\cos \theta) = Q_e^2 Q_\mu^2 (1 + \cos^2 \theta) = (1 + \cos^2 \theta)$$

$$F_{\gamma Z} (\cos \theta) = \frac{Q_e Q_\mu}{4 \sin^2 \theta_w \cos^2 \theta_w} \left[ 2 g_\nu^2 g_\chi^2 (1 + \cos^2 \theta) + 4 g_\nu^2 g_\chi^2 \cos \theta \right]$$

$$F_Z (\cos \theta) = \frac{1}{16 \sin^2 \theta_w \cos^2 \theta_w} \left[ g_\nu^2 + g_\chi^2 \right] \left[ (g_\nu^2 + g_\chi^2)(g_\nu^2 + g_\chi^2)(1 + \cos^2 \theta) + 8 g_\nu^2 g_\chi^2 \cos \theta \right]$$

Forward-backward asymmetry

$$\frac{d\sigma}{d\cos \theta} \sim (1 + \cos^2 \theta) + \frac{8}{3} A_{FB} \cos \theta$$

with $A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$
At the Z-pole $\sqrt{s} \approx M_Z$ → $Z$ contribution is dominant
→ interference vanishes

$$\sigma_{\text{tot}} \approx \sigma_Z = \frac{4\pi}{3s} \frac{\alpha^2}{16\sin^4 \theta_w \cos^4 \theta_w} \frac{\left[g^2_v + g^2_A\right]}{s - M_Z^2} \frac{1}{\left[(s - M_Z^2)^2 + (M_Z \Gamma_Z)^2\right]}$$

"Massive propagator" → 1 for $M_Z \to 0$

$$\sigma_Z(\sqrt{s} = M_Z) = \frac{12\pi \Gamma_\mu \Gamma_\mu}{M_Z^2 \Gamma_Z^2}$$

With partial and total widths:

$$\Gamma_i = \frac{\alpha M_Z}{4} \frac{\sin^2 \theta_w \cos^2 \theta_w}{\sin^4 \theta_w \cos^4 \theta_w} \left[g^2_v + g^2_A\right]$$

$$\Gamma_Z = \sum_i \Gamma_i$$

2.2 Measurement of the Z lineshape

Resonance curve:

$$\sigma(s) = 12\pi \frac{\Gamma_\mu \Gamma_\mu}{M_Z^2} \frac{s}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$

Peak:

$$\sigma_0 = 12\pi \frac{\Gamma_\mu \Gamma_\mu}{M_Z^2} \frac{M_Z^2}{\Gamma_Z^2}$$

- Resonance position $\to M_Z$
- Height $\to \Gamma_\mu$
- Width $\to \Gamma_Z$

Initial state Bremsstrahlung corrections

$$\sigma_{\text{Brem}} = \frac{1}{4\pi} G(z) \sigma^0(zs) dz \quad z = 1 - \frac{2E^2}{\sqrt{s}}$$
Resonance looks the same, independent of final state: Propagator the same

$t$ channel contribution $\rightarrow$ forward peak

$s$ channel
Z line shape parameters (LEP average)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_Z$</td>
<td>$91.1876 \pm 0.0021$ GeV</td>
<td>$\pm 23$ ppm (*)</td>
</tr>
<tr>
<td>$\Gamma_Z$</td>
<td>$2.4952 \pm 0.0023$ GeV</td>
<td>$\pm 0.09$ %</td>
</tr>
<tr>
<td>$\Gamma_{\text{had}}$</td>
<td>$1.7458 \pm 0.0027$ GeV</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_e$</td>
<td>$0.08392 \pm 0.00012$ GeV</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_\mu$</td>
<td>$0.08399 \pm 0.00018$ GeV</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_\tau$</td>
<td>$0.08408 \pm 0.00022$ GeV</td>
<td></td>
</tr>
</tbody>
</table>

3 leptons are treated independently

Assuming lepton universality: $\Gamma_e = \Gamma_\mu = \Gamma_\tau$

*) error of the LEP energy determination: $\pm 1.7$ MeV (19 ppm)

http://lepewwg.web.cern.ch/ (Summer 2005)

LEP energy calibration: Hunting for ppm effects

Changes of the circumference of the LEP ring changes the energy of the electrons:

- tide effects
- water level in lake Geneva

Changes of LEP circumference $\Delta C = 1 \ldots 2$ mm/27 km ($4 \ldots 8 \times 10^{-8}$)

The total strain is $4 \times 10^{-8}$ ($\Delta C = 1$ mm)
Effect of the French "Train a Grande Vitesse" (TGV)

In conclusion: Measurements at the ppm level are difficult to perform. Many effects must be considered!

2.3 Number of light neutrino generations

In the Standard Model:

\[ \Gamma_Z = \Gamma_Z + 3 \cdot \Gamma_\ell + N_\nu \cdot \Gamma_\nu \]

invisible : \[ \Gamma_{inv} \]

\[ \Gamma_{inv} = 0.4990 \pm 0.0015 \text{ GeV} \]

To determine the number of light neutrino generations:

\[ N_\nu = \left( \frac{\Gamma_{inv}}{\Gamma_\ell} \right)_{exp} \cdot \left( \frac{\Gamma_\ell}{\Gamma_\nu} \right)_{SM} \]

5.9431±0.0163 =1.991±0.001 (small theo. uncertainties from m_{top}, M_H)

\[ N_\nu = 2.9840 \pm 0.0082 \]

No room for new physics: Z→new
2.4 Forward-backward asymmetry and fermion couplings to Z

\[ e^+ e^- \rightarrow Z \rightarrow \mu^+ \mu^- \]

\[ \frac{d\sigma}{d\cos\theta} \sim (1 + \cos^2\theta) \frac{8}{3} A_{FB} \cos\theta \]

with \[ A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \]

\[ \sigma_F(\theta) = \int_{0}^{1} d\sigma \frac{d}{d\cos\theta} \]

\[ \sigma_F \]

\[ \sigma_F \]

\[ \sigma_F \]

Fermion couplings

Forward-backward asymmetry

- Away from the resonance $A_{FB}$ large
  → interference term dominates
  
  $A_{FB} \sim g_A^2 g'_A \frac{s(s - M_Z^2)}{(s - M_Z^2)^2 + M_W^2 M_Z^2}$

- At the Z pole: Interference = 0
  
  $A_{FB} \sim g_A^2 g'_A g^2 \frac{1}{2}$
  
  → very small because $g_A^2$ small in SM

Asymmetries together with cross sections allow the determination of the fermion couplings $g_A$ and $g_V$

Lowest order SM prediction:

$g_V = T_3 - 2q \sin^2 \theta_W \quad g_A = T_3$

Confirms lepton universality

Higher order corrections seen
3. Precision tests of the W sector (LEP and Tevatron)

\[ e^+e^- \rightarrow WW \rightarrow fff \]

Threshold behavior of the cross section (phase space) for \( ee \rightarrow WW \) production:

\[
\text{Phase space factor} = f(M_W, \sqrt{s}): \\
\rightarrow \text{Allows determination of } M_W \\
\]

W decays

\[ WW \rightarrow \{ qqlv \ 44\% \\
qqqq \ 45\% \\
l\ell\nu \ 11\% \]
W branching ratios

\[
\text{ALEPH} \quad 10.95 \pm 0.31 \\
\text{DELPHI} \quad 10.55 \pm 0.34 \\
\text{L3} \quad 10.40 \pm 0.30 \\
\text{OPAL} \quad 10.40 \pm 0.33 \\
\text{LEP} \quad 10.59 \pm 0.17 \\
\text{ALEPH} \quad 11.11 \pm 0.29 \\
\text{DELPHI} \quad 10.65 \pm 0.27 \\
\text{L3} \quad 8.72 \pm 0.31 \\
\text{OPAL} \quad 10.61 \pm 0.32 \\
\text{LEP} \quad 10.55 \pm 0.16 \\
\text{ALEPH} \quad 10.67 \pm 0.38 \\
\text{DELPHI} \quad 11.48 \pm 0.43 \\
\text{L3} \quad 11.78 \pm 0.43 \\
\text{OPAL} \quad 11.18 \pm 0.48 \\
\text{LEP} \quad 11.20 \pm 0.22 \\
\text{LEP} \quad 10.74 \pm 0.09 \quad Br(W \to q\bar{q}) = (67.77 \pm 0.28)\% \\
\]

Lepton universality tested to 2%
Effect of triple gauge coupling

Data confirms the existence of the $\gamma/ZWW$ triple gauge boson vertex

4. Higher order corrections and the Higgs mass

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} = 1 \quad \Rightarrow \quad \hat{\rho} = 1 + \Delta \rho$$

$$\sin^2 \theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \Rightarrow \quad \sin^2 \theta_W = (1 + \Delta \kappa) \sin^2 \theta_W$$

$$m_W^2 = \frac{\pi \alpha}{\sqrt{2} \sin^2 \theta_W G_F} \quad \Rightarrow \quad m_W^2 = \frac{\pi \alpha}{\sqrt{2} \sin^2 \theta_W G_F} (1 + \Delta r)$$

$$\alpha(m_W^2) = \frac{\alpha(0)}{1 - \Delta \alpha} \quad \Rightarrow \quad \alpha(m_W^2) = \Delta \alpha \text{lep} + \Delta \alpha \text{top} + \Delta \alpha \text{had}$$

$$\Delta \rho, \Delta \kappa, \Delta r = f \left( m_h^2, \log(m_h), \ldots \right)$$
Top mass prediction from radiative corrections

The measurement of the radiative corrections:

\[ \sin^2 \theta_{\text{eff}} = \frac{1}{4} \left(1 - \frac{g_\gamma}{g_W}\right) \]

\[ \sin^2 \theta_{\text{eff}} = (1 + \Delta \kappa) \sin^2 \theta_w \]

Allows the indirect determination of the unknown parameters \( m_t \) and \( M_H \).

Good agreement between the indirect prediction of \( m_t \) and the value obtained in direct measurements confirm the radiative corrections of the SM.

Prediction of \( m_t \) by LEP before the discovery of the top at TEVATRON.

Observation of the top quark at TEVATRON (1995)

Channel used for mass reconstruction:

\[ m_t = m_{\text{inv}}(b - jet, W \rightarrow jet + jet) \]
5. Higgs searches at the LHC (pp collider @ 14 TeV)

Only missing ingredient of the Standard Model: Higgs-Boson

Higgs Production mechanism:

Huge effort to find it
Higgs decay channels

At LEP: Searches were done using

\[ H \rightarrow b \bar{b} \quad M_H > 114 \text{ GeV} \]

("golden" Higgs decay channel at LEP energies because of large b mass → too much background at LHC)

At LHC:

- \( m_H < 150 \text{ GeV} \): \( H \rightarrow \gamma\gamma \)
- \( 150 \text{ GeV} < m_H < 1 \text{ TeV} \)
  \[ H \rightarrow ZZ^{(*)} \]
  \[ H \rightarrow W'W'^* \]

Simulated \( H \rightarrow ZZ \rightarrow 4\mu \) event at LHC

- 20 pp interaction / event
- Large number of particles

To trigger and to reconstruct these events is an exp. challenge.
If the Higgs Boson exists, it will be found at LHC.

LHC start is foreseen for the end of 2007.