VI. 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

1.1 Boson production in pp interactions

1983 at CERN Sp$ar{p}$S accelerator, $\sqrt{s}$=540 GeV, UA-1/2 experiments

$p\bar{p} \rightarrow W \rightarrow \ell^+\ell^- + X$

$p\bar{p} \rightarrow Z \rightarrow \ell^+\ell^- + X$

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

$\hat{s} = x_q^2 x_{\pi} s$ mit $\langle x_q \rangle \approx 0.12$

$\hat{s} = \langle x_q \rangle^2 s \approx 0.014 s = (65 \text{ GeV})^2$

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

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

High-energy lepton pair:

$$m_{\ell\ell}^2 = (p_{\ell^+} + p_{\ell^-})^2 = M_Z^2$$

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

- Undetected $\nu$: Missing momentum
- High-energy lepton: Large transverse momentum $p_\ell$
- How can the W mass be reconstructed?

**W mass measurement**

In the W rest frame:
- $|\bar{p}| = |\bar{p}_W| = \frac{M_W}{2}$
- $|p_\ell| \leq \frac{M_W}{2}$

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

Jacobian Peak:

$$\frac{dN}{dp_T} \sim \frac{1}{M_W} \left[ \sqrt{M_W^2 - p_T^2} \right]$$

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

$M_W \approx 80$ GeV
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Jacobian Peak

Assume isotropic decay of the W boson (not really correct) in its CM system:

\[
\frac{dN}{d\cos \theta} = \text{const.}
\]

Simplification: W boson has spin=1 → decay is not isotropic!

\[
\sin \theta = \frac{p_T}{p} = \frac{p_T}{M_w/2}
\]

\[
1 - \cos^2 \theta = \left(\frac{p_T}{M_w/2}\right)^2
\]

\[
\frac{dN}{dp_T} = \frac{\rho_T}{M_w^2} \left(\frac{M_w^2}{4} - p_T^2\right)^{-1/2}
\]

\[
d\cos \theta \sim \frac{p_T}{(M_w/2)^2} \frac{dp_T}{\cos \theta}
\]

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"

S. van der Meer

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

![Graph showing production of Z and W bosons in $e^+e^-$ annihilation](image)

#### 2. Precision tests of the Z sector

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

\[ \left| M \right|^2 = \left( \begin{array}{c} \gamma \\ Z \end{array} \right) + \left( \begin{array}{c} Z \\ \gamma \end{array} \right) \]

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

\[ M_f = -e^2(\pi \gamma,\mu) \frac{1}{q^2}(\pi \gamma,e) \]

\[ M_Z = -\frac{g^2}{\cos^2\theta_W} \left[ \pi \gamma,\nu (g^\nu - g^\nu g^\nu) \mu \right] \left( g_{\mu\nu} - q_{\mu} q_{\nu} / M_Z^2 \right) \left( q^2 - M_Z^2 \right) \left( q^2 - M_Z^2 \right) \left( q^2 - M_Z^2 \right) \left( q^2 - M_Z^2 \right) \left( q^2 - M_Z^2 \right) \left( q^2 - M_Z^2 \right) \]

Z propagator considering a finite Z width at resonance

\[ \sim 4.5M \text{ decays} / \text{ experiment} \]

\[ \text{LEP and SLC} \]

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One finds for the differential cross section:

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

\[ \gamma \quad \text{\gamma/Z interference} \quad Z \]

Vanishes at \( \sqrt{s} = M_Z \)

\[ F_i(\cos\theta) = Q_i^2 Q_i^\prime(1 + \cos^2 \theta) \]

\[ F_Z(\cos\theta) = \frac{Q_i Q_i^\prime}{4 \sin^2 \theta_W \cos^2 \theta_W} \left[ 2 g_{\gamma\gamma}^\mu(1 + \cos^2 \theta) + 4 g_{\mu\mu}^\gamma \cos\theta \right] \]

\[ F_{\pm}(\cos\theta) = \frac{1}{16 \sin^4 \theta_W \cos^4 \theta_W} \left[ (g_{\nu\nu}^\mu + g_{A}^\mu)(g_{\nu\nu}^\mu + g_{A}^\mu)(1 + \cos^2 \theta) + 8 g_{\nu\nu}^\mu g_{\gamma\gamma}^\mu \cos\theta \right] \]

Forward-backward asymmetry:

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

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

\[ \sigma_F^{(B)} = \int_{0.1-1} d\sigma d\cos\theta \]

At the Z-pole \( \sqrt{s} \approx M_Z \)

\( \rightarrow \) Z contribution is dominant

\( \rightarrow \) interference vanishes

\[ \sigma_{tot} \approx \sigma_Z = \frac{4\pi}{3s} \alpha^2 \frac{\sin^4 \theta_W \cos^4 \theta_W}{16} \left[ (g_{\nu\nu}^\mu)^2 + (g_{A}^\mu)^2 \right] \left[ (g_{\nu\nu}^\mu)^2 + (g_{A}^\mu)^2 \right] \cdot \frac{s^2}{(s-M_Z^2)^2 + (M_Z^2\Gamma_Z^2)^2} \]

\[ A_{FB} = 3 \cdot \frac{g_{\gamma\gamma}^\mu}{(g_{\nu\nu}^\mu)^2 + (g_{A}^\mu)^2} \cdot \frac{g_{\nu\nu}^\mu g_{A}^\mu}{(g_{\nu\nu}^\mu)^2 + (g_{A}^\mu)^2} \]
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At the Z-pole $\sqrt{s} \approx M_Z$ → Z contribution is dominant
→ interference vanishes

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

Cross sections and widths can be calculated within the Standard Model if all parameters are known.

2.2 Measurement of the Z lineshape

Z Resonance curve:

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

Peak:

$$\sigma_0 = 12\pi \frac{\Gamma_\mu \Gamma_e}{M_Z^2} \frac{1}{\Gamma_Z^2}$$

- Resonance position → $M_Z$
- Height → $\Gamma_\mu \Gamma_e$
- Width → $\Gamma_Z$

Initial state Bremsstrahlung corrections

$$\sigma_{\mu(\nu)} = \frac{1}{4\pi} G(z) \sigma_0(z) dz \quad z = 1 - \frac{2E_z}{\sqrt{s}}$$
Resonance shape is the same, independent of final state: Propagator the same!
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Z line shape parameters (LEP average)

\[
\begin{align*}
M_Z &= 91.1876 \pm 0.0021 \text{ GeV} \\
\Gamma_Z &= 2.4952 \pm 0.0023 \text{ GeV} \\
\Gamma_{\text{had}} &= 1.7458 \pm 0.0027 \text{ GeV} \\
\Gamma_e &= 0.08392 \pm 0.00012 \text{ GeV} \\
\Gamma_\mu &= 0.08399 \pm 0.00018 \text{ GeV} \\
\Gamma_\tau &= 0.08408 \pm 0.00022 \text{ GeV} \\
\Gamma_Z &= 2.4952 \pm 0.0023 \text{ GeV} \\
\Gamma_{\text{had}} &= 1.7444 \pm 0.0022 \text{ GeV} \\
\Gamma_e &= 0.083985 \pm 0.000086 \text{ GeV} \\
\end{align*}
\]

\(\pm 0.09\%\)

Assuming lepton universality: \(\Gamma_e = \Gamma_\mu = \Gamma_\tau\)

3 leptons are treated independently

\(\pm 0.23\text{ ppm (*)}\)

\(\pm 0.09\%\)

\(\pm 0.09\%\)

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

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 \(\Delta C = 1…2 \text{ mm/27km (4…8x10^{-8})}\)

The total strain is \(4 \times 10^{-6}\) (\(\Delta C = 1 \text{ mm}\))

1992 Effect of moon

1993 Effect of lake

1999 LEP run

Correlates with lake level...

"Heavy" Rainfall

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**Effect of the French "Train a Grande Vitesse" (TGV)**

Vagabonding currents (~1A) from trains

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:

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

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

To determine the number of light neutrino generations:

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

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

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

No room for new physics: Z→new
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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

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\sigma_F(\theta) = \int_{0}^{\theta} \frac{d\sigma}{d\cos\theta}$$

Fermion couplings

Forward-backward asymmetry

- Away from the resonance $A_{FB}$ large → interference term dominates
  $$A_{FB} \sim g_A^e g_A^\mu \frac{s(s - M_Z^2)}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$
- At the Z pole: Interference = 0
  $$A_{FB} \sim g_A^e g_A^\mu g_V^e g_V^\mu$$
  → very small because $g_V^\mu$ small in SM

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

Lowest order SM prediction:

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

$$g_A = T_3$$

Confirms lepton universality

Higher order corrections seen