Precision measurements on the Z resonance

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Motivation

18 Standard Model parameters

- 9 charged fermion masses
- 4 quark mixing parameters
- $m_H$
- Coupling constants $\alpha_{\text{QED}}$ and $\alpha_s$
- $(m_W$ and $m_Z$) or $(G_F$ and $\sin \theta_W$)

$G_F = 1.16637(1) \cdot 10^{-5} \text{GeV}^{-2}$

with an uncertainty of 9000ppb
determine $m_Z$ with same precision
precision measurement as fundamental test of Standard Model (SM)

Electroweak interaction

- new quantum number
- weak isospin $T$
- weak hypercharge $Y_W$

- symmetry groups
  - $SU(2)_L$
  - $U(1)_Y$

- generator
  - $W^\mu = (W^1, W^2, W^3)$
  - $B^\mu$

- observable fields
  - charged currents
    - $W^\pm = \frac{1}{\sqrt{2}}(W^1 + iW^2)$
  - neutral current
    - $Z^\mu = \cos \theta_W W^3 + \sin \theta_W B^\mu$
  - photon
    - $A^\mu = \sin \theta_W W^3 + \cos \theta_W B^\mu$

- Gell-Mann- Nishijima formula
  - $Y_W = 2 \left( Q + T_Z \right)$

- coupling constants
  - $g \sin \theta_W = e$
  - $g^* \cos \theta_W = e$

- relationship between charged and neutral weak current

\[ \rho \cos^2 \theta_W = \frac{m^2_W}{m^2_Z} \]
The Z resonance

1983 Z and W discovery at SPS

\[ m_Z = (95.2 \pm 2.5) \text{GeV} \]

\[ m_W = (81 \pm 5) \text{GeV} \]

Z production at LEP in electron-positron annihilation

\[ \sigma \propto |M|^2 = \]

\[ \sigma_\gamma \propto \frac{1}{s} \]

\[ \sigma(\sqrt{s} = m_Z) \approx \frac{12\pi}{m_Z^2} \frac{\Gamma_e \Gamma_f}{\Gamma_Z^2} = \frac{12\pi}{m_Z^2} BR(Z \rightarrow e^+ e^-) \cdot BR(Z \rightarrow f \bar{f}) \]

Breit-Wigner-formula
QED Radiative Corrections

- photon radiation
- initial state bremsstrahlung leads to energy shift of peak cross section
- vertex correction reduces peak cross section to 74%

running of $\alpha$ due to fermion loops

$$\alpha(0) = \frac{1}{137} \rightarrow \alpha(m_Z) = \frac{1}{128}$$
Requirement for Collider

e^+ e^- collider
beam energy of 45 GeV
high luminosity
  • Peak at 2 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}
    \rightarrow 1000 Z bosons per hour per experiment
precise knowledge of beam energy

LEP storage ring 27km circumference
Injection system: SPS

Timetable of LEP

1989  initial run
1990/1991  scan of Z resonance, data taken at peak and ±1,2,3 GeV off peak
1992  data taken on peak
1993  scan of Z resonance, data taken at peak and ±2 GeV off peak
      improvement of beam energy calibration
1994  data taken at peak
1995  scan of Z resonance, data taken at peak and ±2 GeV off peak
      after final run installation of additional superconducting cavities
1996  first run of LEP(II), center-of-mass Energy 161-209 GeV
2000  LEP is shut down to make room for LHC
Large Electron Positron Collider (LEP I)

4-8 bunches á $4 \cdot 10^{11}$ particles
- IP 1, 3, 5, 7 vertical separation of colliding beams
- Bending sections
  - > 3000 dipole magnets providing $B = 0.048$ T
  - quadrupoles and sextupoles for beam focusing and corrections
- RF Cu cavities
  - acceleration form 20 GeV to 45 GeV
  - $f_{RF} \approx 350$ MHz
  - replace 125 MeV energy loss per turn

http://www.swisster.ch/multimedia/images/img_traittees/2008/09/cern0108001_01-a4-at-144-dpi_news_zoom.jpg
Beam energy calibration

bending leads to
• transversal self polarization (Sokolof-Ternov-effect)
• spin precession

\[ \nu_s = \frac{g_e - 2}{2} \frac{E_{beam}}{m_e c^2} = \frac{E_{beam}}{440.6486(1) \text{ MeV}} \]

\( \nu \) measured by resonant depolarization
• external magnetic field applied
→ polarisation is destroyed

calibration run outside data taking
precision on beam energy

\[ \pm 0.2 \text{ MeV} \rightarrow \frac{\Delta E_{beam}}{E_{beam}} < 10^{-5} \]
Luminosity determination

Bhabha scattering

\[
\int L_{Bhabha} dt = L_{int} = \frac{N_{Bhabha}}{\epsilon \sigma_{theo}}
\]

small angle Bhabha scattering

- low momentum transfer, \(\sigma_{theo}\) well-known from QED
- \(\sigma_{theo}\) gives an important theoretical error of about 0.05% common to all experiments
Requirements for detectors

- events
- tracking of charged particles
- measurement of direction and momentum
- particle identification
  - by dE/dx (Bethe-Bloch)
  - total absorption in calorimeter

hadronization
The Omni Purpose Apparatus at LEP

http://www.hep.phy.cam.ac.uk/opal/opal.gif
Event detection

\[ \begin{align*}
\text{e}^+ & \quad \text{e}^- \\
Z^0 & \quad \text{e}^+ \\
\text{e}^- & \quad \text{e}^- \\
\text{e}^+ & \quad \mu^+ \\
\text{e}^- & \quad \mu^- \\
Z^0 & \quad \text{q} \\
\text{e}^- & \quad \text{q}
\end{align*} \]
Total cross section at Z pole

\[ \sigma = \frac{N(1 - b)}{eL_{int}} \]

Z line shape parameters

- \( m_Z \)
- \( \Gamma_Z \)
- \( \Gamma_{hadr} \)
- \( \Gamma_b \)
- \( \Gamma_e \)
- \( \Gamma_{\mu} \), \( \Gamma_{lep} \)
- \( \Gamma_{\tau} \)
Direct measurements

- The mass of the Z boson

\[ m_Z = 91.1875 \pm 0.0021 \text{ GeV} \]

\[ \Delta m_Z = 2.3 \cdot 10^{-5} \]

error dominated by uncertainty in absolute energy scale

- The total width of the Z boson

\[ \Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV} \]

\[ \sum_{q \neq t} \Gamma_{\bar{q}q} = 1.7458 \pm 0.0027 \text{ GeV} \]
leptons' coupling to the gauge bosons flavour dependent?
leptonic widths $\Gamma_e$, $\Gamma_\mu$ and $\Gamma_\tau$ agree better than 0.5% among each other
more sensitive

\[
R_e^0 \equiv \frac{\Gamma_e}{\Gamma_{hadr}} = 20.901 \pm 0.084
\]

\[
R_\mu^0 \equiv \frac{\Gamma_\mu}{\Gamma_{hadr}} = 20.811 \pm 0.058
\]

\[
R_\tau^0 \equiv \frac{\Gamma_\tau}{\Gamma_{hadr}} = 20.832 \pm 0.091
\]

*lepton universality* in weak neutral currents proved
The invisible width \( e^+e^- \rightarrow Z \rightarrow \nu_l\bar{\nu}_l \)

to determine the number of light neutrinos
\[
\Gamma_{inv} = \Gamma_Z - \Gamma_{hadr} - 3\Gamma_l
\]
\[
\Gamma_{inv} = 499.0 \pm 1.5 \text{MeV}
\]
\[
N_{\nu} = \frac{\Gamma_{inv}}{\Gamma_{\nu}} = \frac{\Gamma_{inv}}{\Gamma_l} \left( \frac{\Gamma_l}{\Gamma_{\nu}} \right)^{SM} = 2.9840 \pm 0.0082
\]

strong dependence of hadronic peak cross-section on \( N_{\nu} \)

proves presence of three standard neutrino families
Direct determination of invisible width

\[ e^+ e^- \rightarrow Z \rightarrow \nu_l \bar{\nu}_l \]

contribution of Z exchange \(\sim\) number of light neutrino families
since Z couples equal to all neutrino species (lepton universality)

rules out existence of a fourth generation of neutrinos in the SM

Important test of SM
b-quark identification via lifetime-tagging
unique corrections due to $V_{bt}$

\[
\begin{align*}
\text{ratio} & \quad R_b = \frac{\Gamma_b}{\Gamma_{had}} \\
\text{depends} & \quad m_t, \text{ independent of } \alpha_s \text{ and } m_H \\
\text{LEP value} & \quad R_b = 0.2205 \pm 0.0016 \\
\text{SM value} & \quad (R_b)^{SM} = 0.2157
\end{align*}
\]
Weak radiative corrections

- $G_F$ out of muon lifetime treated as a constant
- $W^\pm$ vacuum polarization
- Coupling to Higgs field

- P parameter, ratio of neutral and charged currents, is modified

$$\rho = 1 + \Delta \rho$$

Corrections arising from propagator self-energies

$$\Delta \rho_{se} = \frac{3 G_F m_W^2}{8 \sqrt{2} \pi^2} \left[ \frac{m_t^2}{m_W^2} - \frac{\sin^2 \vartheta_W}{\cos^2 \vartheta_W} \left( \ln \frac{m_H^2}{m_W^2} - \frac{5}{6} \right) \right]$$

- Allows an indirect determination of the unknown parameters $m_t$ and $m_W$
Mass of the Top Quark

indirect constrain
\[ m_t = 173^{+13}_{-10} \text{GeV} \]

direct measurement
\[ m_t = 178.0 \pm 4.3 \text{GeV} \]
Mass of the W Boson

prediction

\[ m_W = 80.363 \pm 0.032 \text{GeV} \]

direct measurement and prediction agree very well

Test of SM and its predictive power
The Higgs boson

LEP II: $114.4 \text{ GeV} < m_H$

upper limit on $\log_{10}(m_H/\text{GeV})$:

$m_H < 285 \text{ GeV}$

consistent with 95% confidence level

Comparison of direct and indirect measurements of $m_t$ and $m_W$. The green shows the SM prediction.
QCD Corrections

gluon exchange or radiation

rate of 3 jet events depends on $\alpha_s$

modification of hadronic cross section and decay width as a function of $\alpha_s$

use to determine coupling
Determination of Strong Coupling Constant

\[ \frac{R_l}{R_{\text{lep}}} = 20.788 \pm 0.032 \]

weak radiative corrections cancel

\[ R_l = 19.943\left[1 + 1.060\frac{\alpha_s}{\pi} + 0.90\left(\frac{\alpha_s}{\pi}\right)^2 - 15\left(\frac{\alpha_s}{\pi}\right)^3\right] \]

\[ \alpha_s = 0.124 \pm 0.005 \pm 0.005 \]

out of 3-jet events

\[ \alpha_s(m_z) = 0.124 \pm 0.021 \]
Summary

approximately 14 mio. Z decays

\begin{align*}
\text{Z boson mass} & \quad m_Z = 91.1875 \pm 0.0021 \text{ GeV} \\
\text{Z decay width} & \quad \Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV} \\
\text{lepton universality} & \\
\text{number of light neutrinos} & \quad N_\nu = 2.9840 \pm 0.0082 \\
\text{W boson mass} & \quad m_W = 80.363 \pm 0.032 \text{ GeV} \quad m_W^{2008} = 80.398 \pm 0.032 \text{ GeV} \\
\text{top quark mass} & \quad m_t = 173^{+13}_{-10} \text{ GeV} \quad m_t^{2008} = 171.2 \pm 2.1 \text{ GeV} \\
\text{mass of Higgs boson} & \quad 114 \text{ GeV} < m_H < 285 \text{ GeV}
\end{align*}

SM verified to be a good theory up to 100 GeV
References


[2] Joachim Mnich, "Experimental Test of the Standard Model in $e^+e^- \rightarrow f\bar{f}$ at the Z resonance”,

[3] Ralph Aßmann, "Optimierung der transversalen Spin-Polarisation im LEP-Speicherring und Anwendung für Präzisionsmessungen am Z-Boson”


