Precision measurements on the Z resonance

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Seminar „Key Experiments in Particle Physics“

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Electroweak Theory

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Summary

Motivation

18 Standard Model parameters

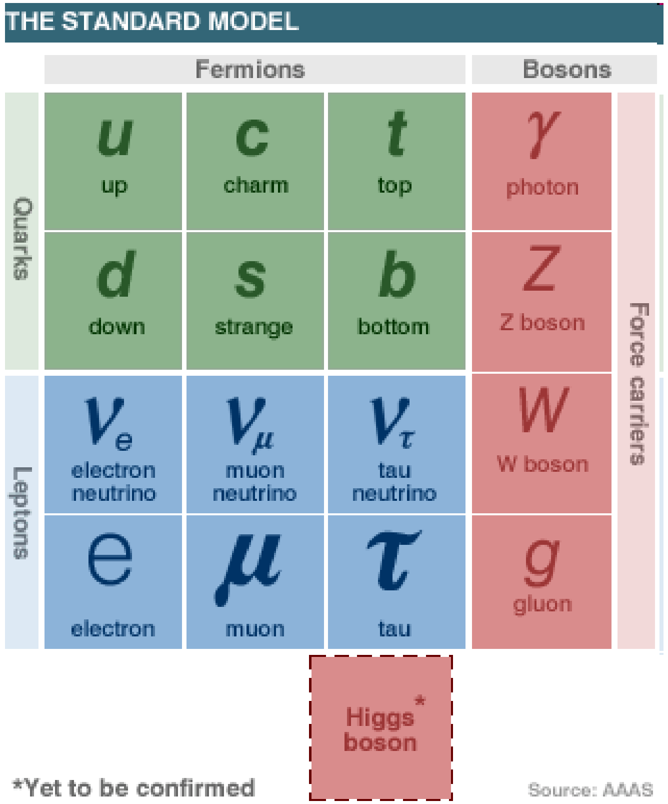
- 9 charged fermion masses
- 4 quark mixing parameters
- m_H
- Coupling constants α_{QED} and α_s
- (m_W and m_Z) or (G_F and $\sin\theta_W$)

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

with an uncertainty of 9000ppb

determine m_Z with same precision

precision measurement as fundamental test of Standard Model (SM)



http://gabrielbcn.files.wordpress.com/2007/07/standard_model_316.gif

Electroweak interaction

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

$$Y_W = 2\,(Q + T_Z)$$

Gell-Mann- Nishijima formula

- symmetry groups — generator
  - $SU(2)_L$ — $W_\mu = (W^1, W^2, W^3)$
  - $U(1)_Y$ — B_μ

coupling constants

$g \sin\theta_W = e$

$g' \cos\theta_W = e$

- observable fields

charged currents $$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2)$$

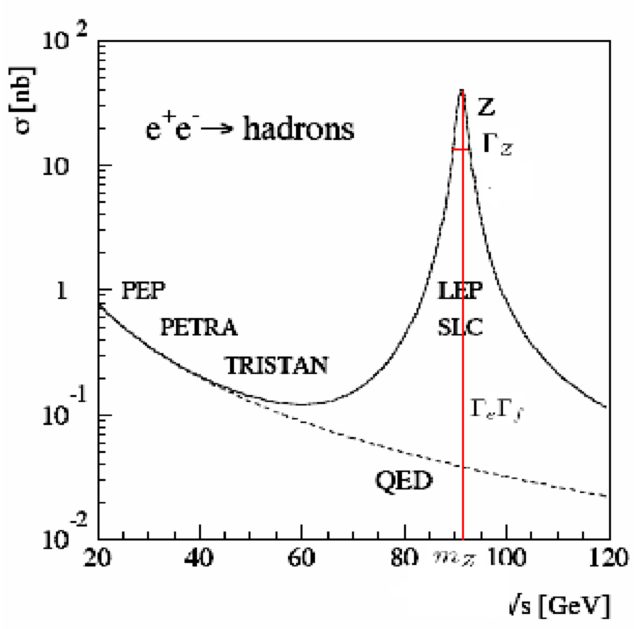
neutral current $$Z_\mu = \cos\theta_W W_\mu^3 - \sin\theta_W B_\mu$$

photon $$A_\mu = \sin\theta_W W_\mu^3 + \cos_W B_\mu$$

- relationship between charged and neutral weak current

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

The Z resonance



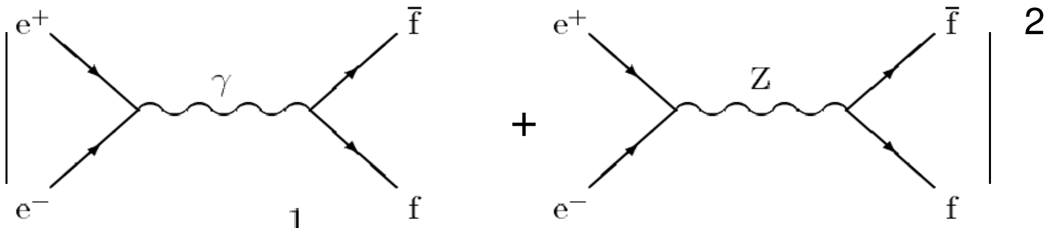
1983 Z and W discoverv at SPS

$$m_Z = (95.2 \pm 2.5) GeV$$

$$m_W = (81 \pm 5) GeV$$

Z production at LEP in electron-positron annihilation

$$\sigma \propto |M|^2 =$$



$$\sigma_\gamma \propto \frac{1}{s}$$

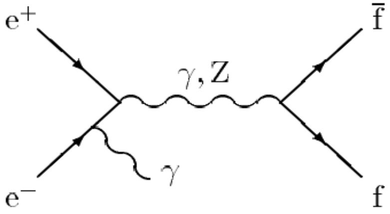
dominates at Z pole

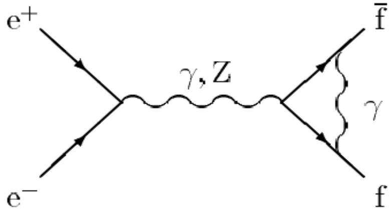
$$\sigma(\sqrt{s} = m_Z) \approx \frac{12\pi}{m_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2} = \frac{12\pi}{m_Z^2} BR(Z \to e^+e^-) \cdot BR(Z \to f\bar{f})$$

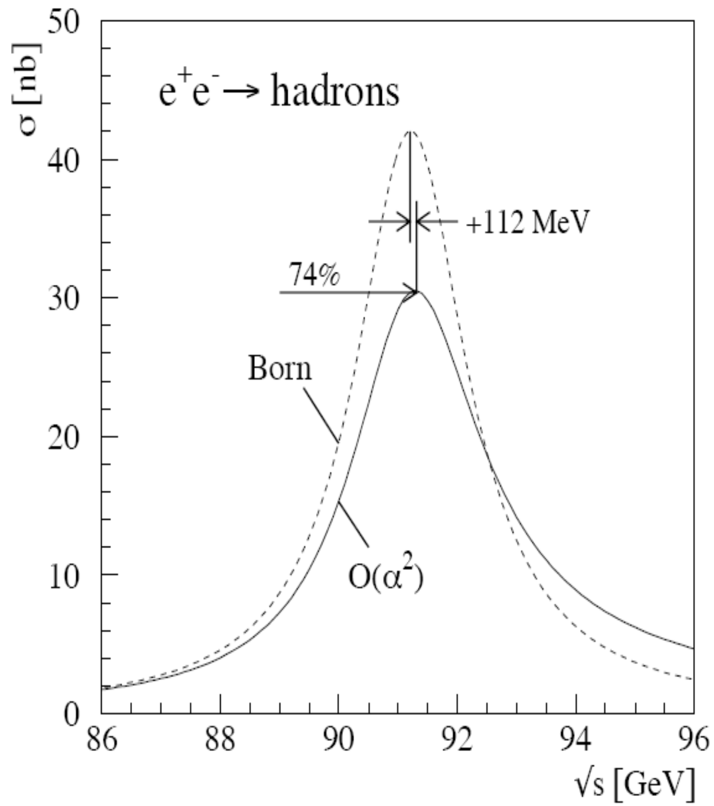
Breit-Wigner-formula

QED Radiative Corrections

photon radiation

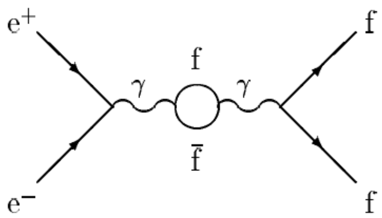






- initial state bremststahlung leads to energy shift of peak cross section
- vertex correction reduces peak cross section to 74%

running of α 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

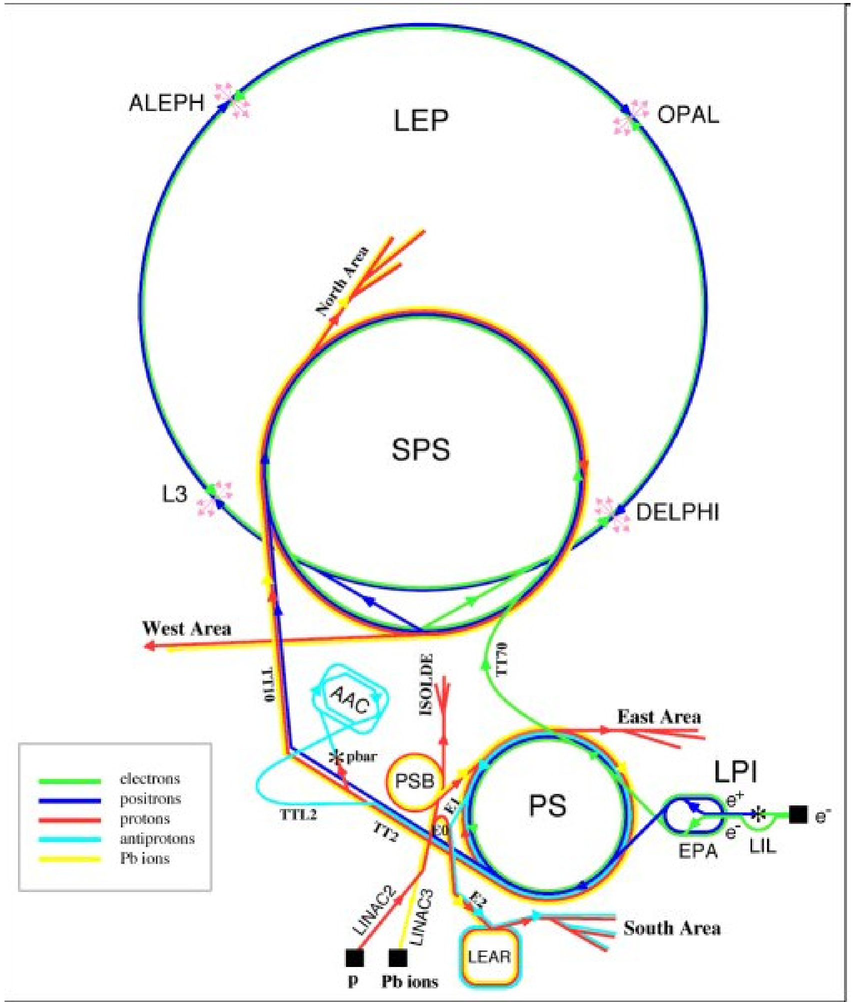
- Peak at $2\ 10^{31} cm^{-2} s^{-1}$

  → 1000 Z bosons per hour per experiment

precise knowledge of beam energy

LEP storage ring 27km circumference

Injection system: SPS



http://universe-review.ca/R15-15-LEP.htm

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

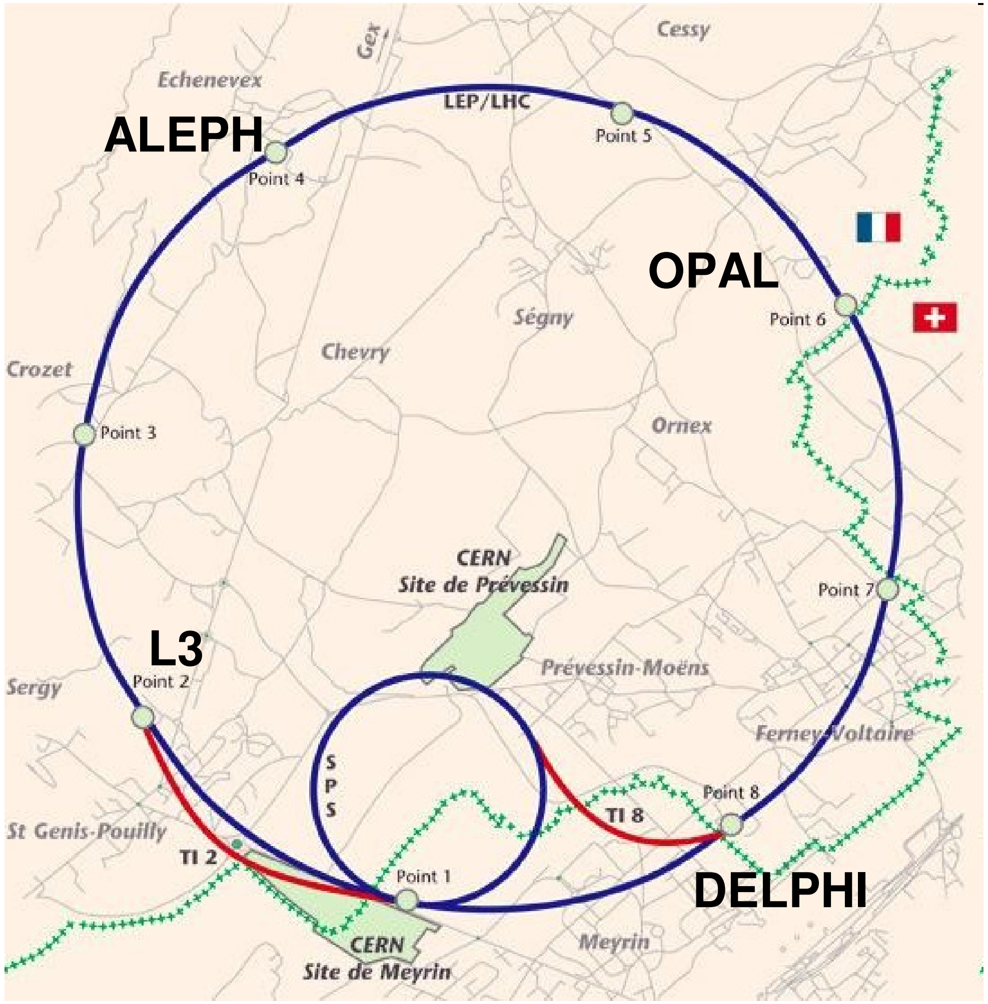
Bending sections

- > 3000 dipole magnets providing B = 0.048 T

quadru- and sextupoles for beam focusing and corrections

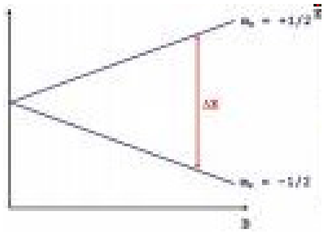
RF Cu cavities

- acceleration form 20GeV to 45 GeV
- $f_{RF} \approx 350$ MHz
- replace 125 MeV energy loss per turn



http://www.swisster.ch/multimedia/images/img_traitees/2008/09/cern0108001_01-a4-at-144-dpi_news_zoom.jpg

Beam energy calibration



bending leads to

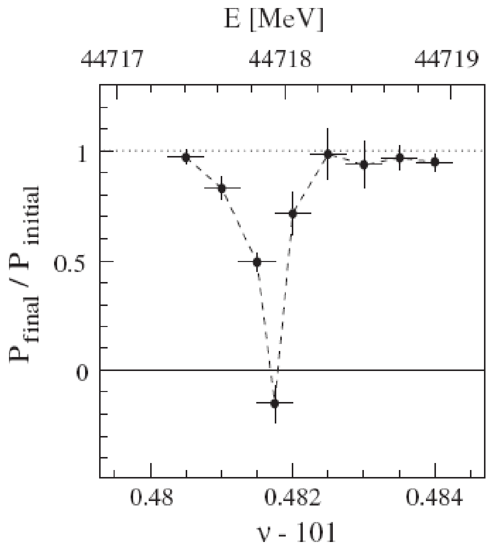
- transversal self polarization (Sokolof-Ternov-effect)
- spin precession

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

ν measured by resonant depolarization

- external magentic field applied

→ polarisation is destroyed



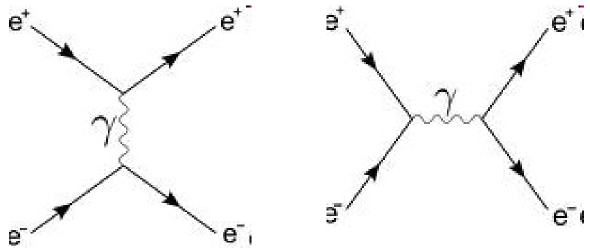
calibration run outside data taking

precision on beam energy

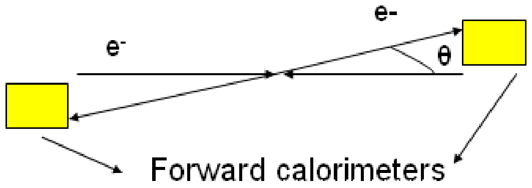
$$\pm 0.2 MeV \rightarrow \frac{\Delta E_{beam}}{E_{beam}} < 10^{-5}$$

Luminosity determination

Bhabha scattering

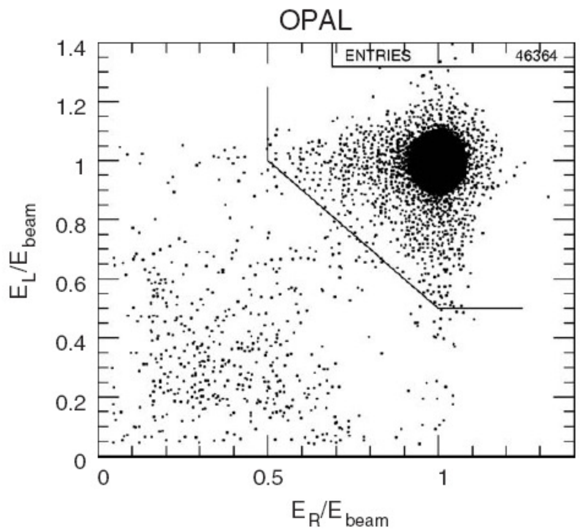


$$\int L_{Bhabha} dt = L_{int} = \frac{N_{Bhabha}}{\epsilon \sigma_{theo}}$$



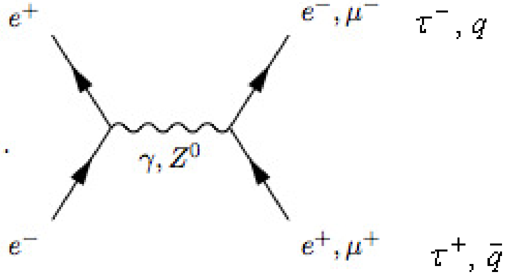
small angle Bhabha scattering

- low momentum transfer, σ_{theo} well- known from QED
- σ_{theo} gives an important theoretical error of about 0.05% common to all experiments



Requirements for detectors

events



$$
\begin{aligned}
Z &\rightarrow e^+e^- \\
Z &\rightarrow \mu^+\mu^- \\
Z &\rightarrow \tau^+\tau^- \\
Z &\rightarrow \nu\overline{\nu}
\end{aligned}
\qquad
\begin{aligned}
Z &\rightarrow u\overline{u} \\
Z &\rightarrow d\overline{d} \\
Z &\rightarrow c\overline{c} \\
Z &\rightarrow s\overline{s} \\
Z &\rightarrow b\overline{b}
\end{aligned}
\quad \Rightarrow \quad \text{hadronization}
$$

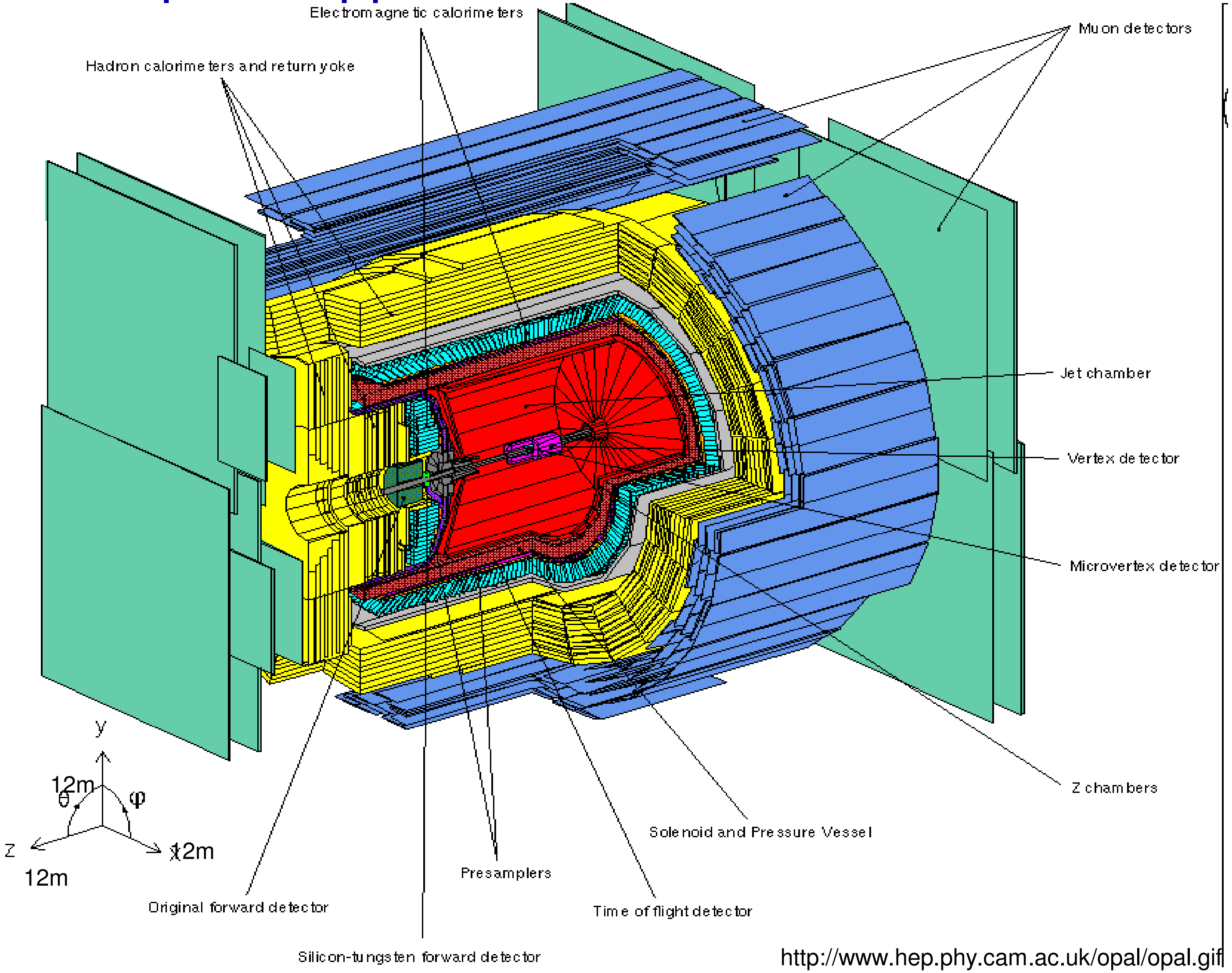
tracking of charged particles

- measurement of direction and momentum

particle identification

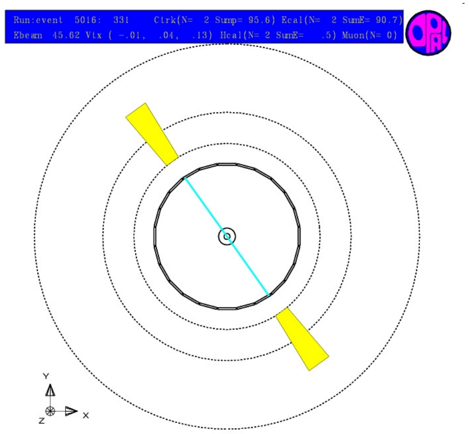
- by dE/dx (Bethe-Bloch)
- total absorption in calorimeter

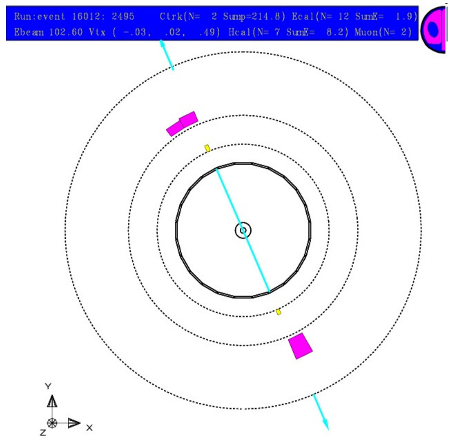
The Omni Purpose Apparatus at LEP

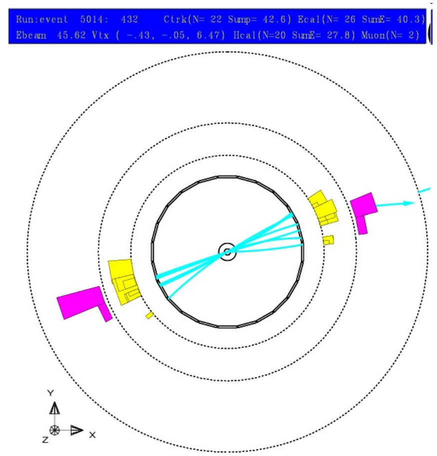


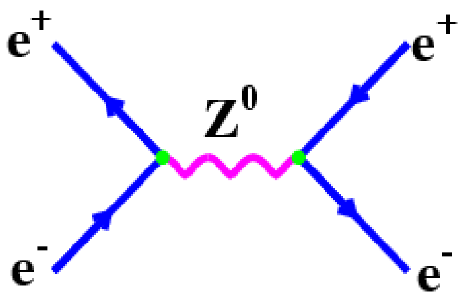
http://www.hep.phy.cam.ac.uk/opal/opal.gif

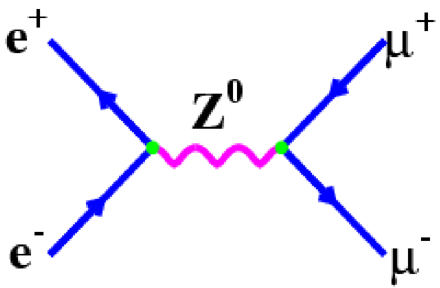
Event detection

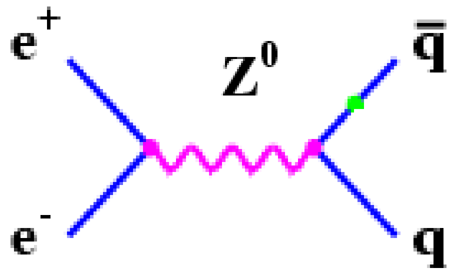












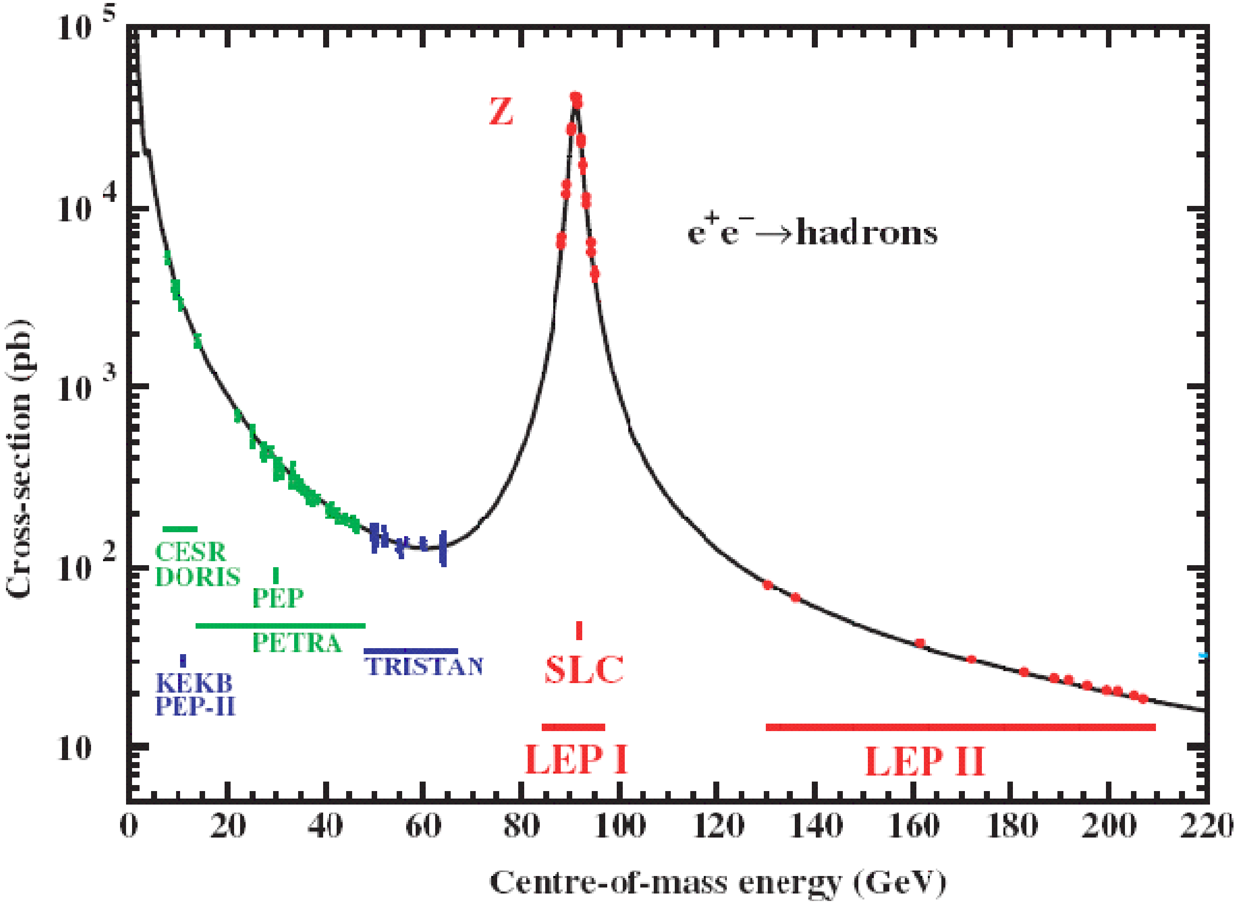
Total cross section at Z pole

$$\sigma = \frac{N(1-b)}{\epsilon L_{int}}$$

Z line shape parameters

- m_Z
- Γ_Z
- Γ_{hadr}
- Γ_b
- Γ_e
- Γ_μ
- Γ_τ

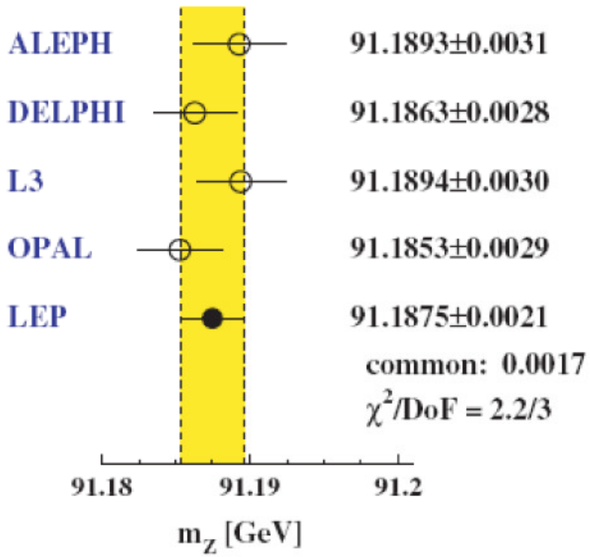
Γ_{lep}



Direct measurments

- The mass of the Z boson

$$m_Z = 91.1875 \pm 0.0021 GeV$$

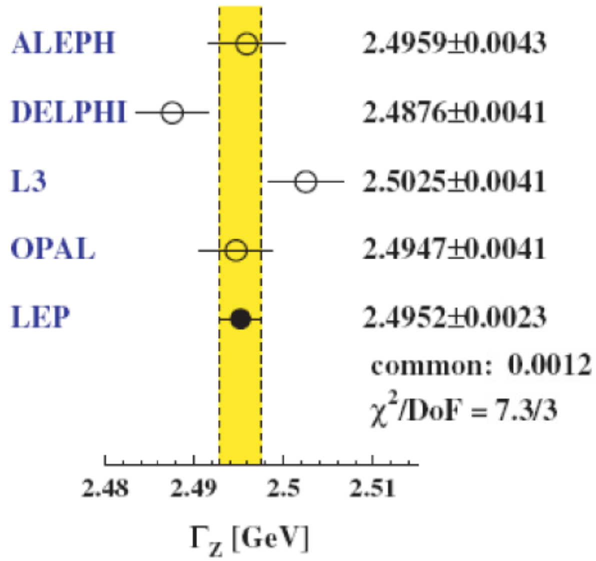


$$\frac{\Delta m_Z}{m_Z} = 2.3 \cdot 10^{-5}$$

error dominated by uncertainty in absolute energy scale

- The total width of the Z boson

$$\Gamma_Z = 2.4952 \pm 0.0023 GeV$$



- partial width into hadrons $\sum_{q \neq t} \Gamma_{\bar{q}q}$

$$\Gamma_{hadr} = 1.7458 \pm 0.0027 GeV$$

Partial width into leptons

leptons‘ coupling to the gauge bosons flavour dependent ?

leptonic widths Γ_e, Γ_μ and Γ_τ agree better than 0.5% among eacht 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 universalitiy in weak neutral currents proved

The invisible width $e^+e^- \to Z \to \nu_l \overline{\nu_l}$

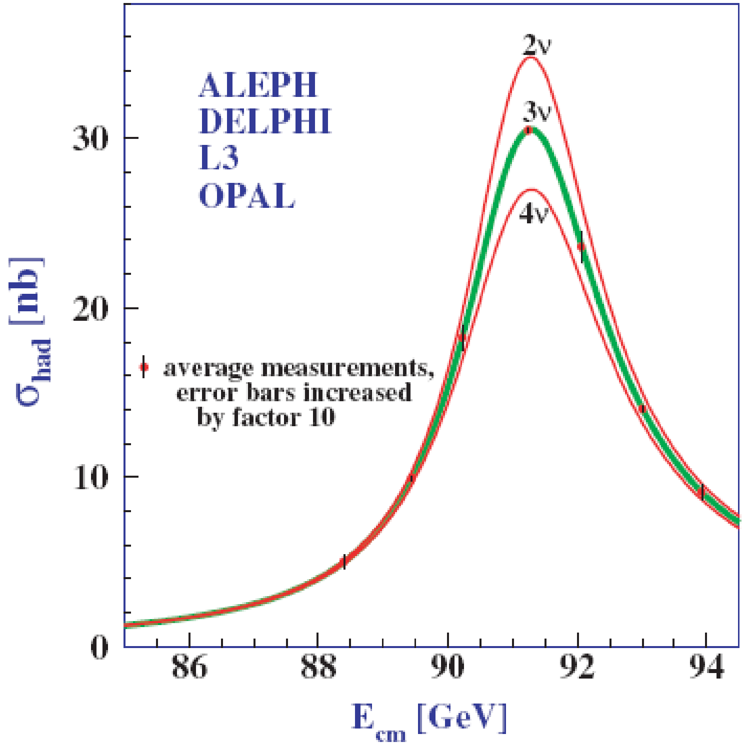
to determine the number of light neutrinos

$$\Gamma_{inv} = \Gamma_Z - \Gamma_{hadr} - 3\Gamma_l$$

$$\Downarrow$$

$$\Gamma_{inv} = 499.0 \pm 1.5 MeV$$

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_\nu} = \frac{\Gamma_{inv}}{\Gamma_l}\left(\frac{\Gamma_l}{\Gamma_\nu}\right)^{SM} = 2.9840 \pm 0.0082$$

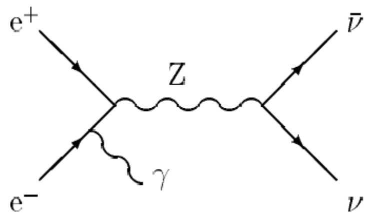


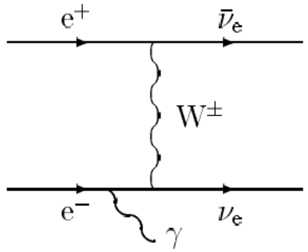
strong dependence of hadronic peak cross-section on N_ν

proves presence of three standard neutrino families

Direct determination of invisible width

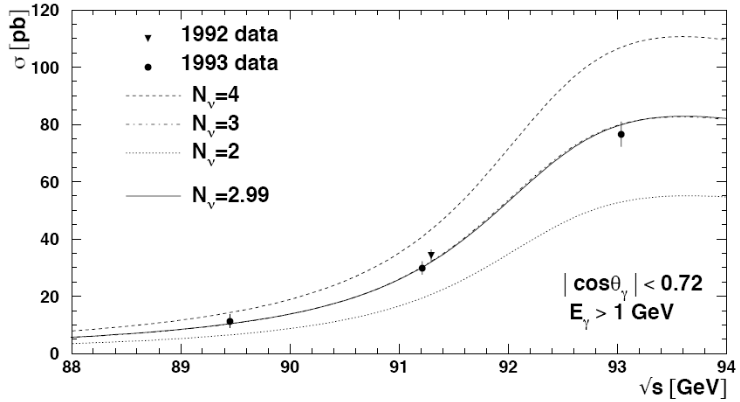
$$e^+e^- \rightarrow Z \rightarrow \nu_l\overline{\nu_l}$$





contribution of Z exchange ~ number of light neurtino families

since Z couples equal to all neutrino species (*lepton universality*)



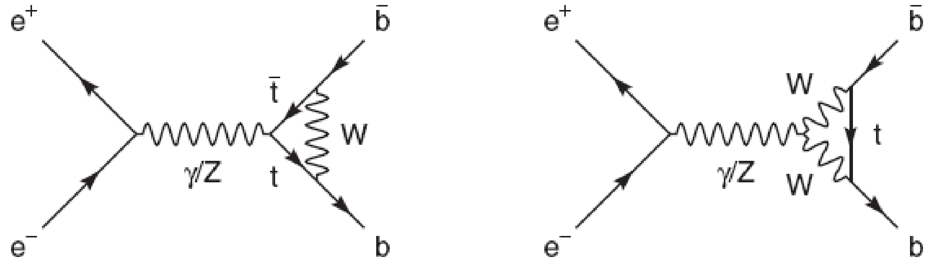
rules out existence of a fourth generation of neutrinos in the SM

Important test of SM

Partial Width $Z \to b\bar{b}$

b-quark identification via lifetime-tagging

unique corrections due to V_{bt}



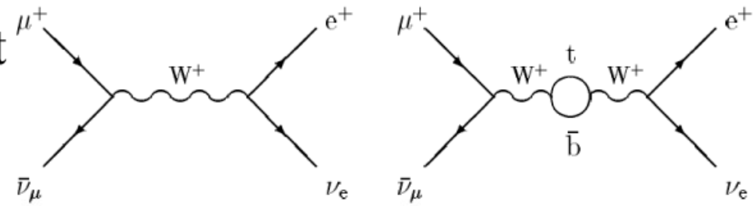
ratio $R_b = \frac{\Gamma_b}{\Gamma_{had}}$ depends m_t, independent of α_s and m_H

LEP value $R_b = 0.2205 \pm 0.0016$

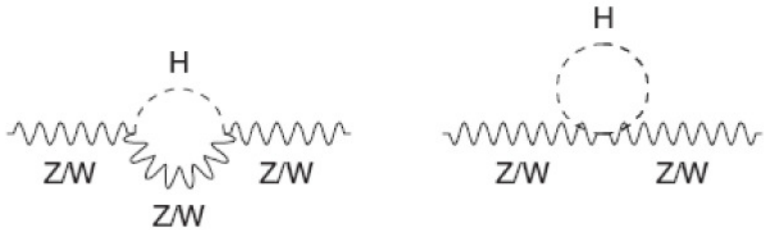
SM value $(R_b)^{SM} = 0.2157$

Weak radiative corrections

- G_F out of muon lifetime treated as a constant
- $W^{\pm}$ vakuum polarization



- coupling to Higgs field



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

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

corrections arising from propagator self energies

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

- allows an indirect determination of the unknown paramters m_t and m_W

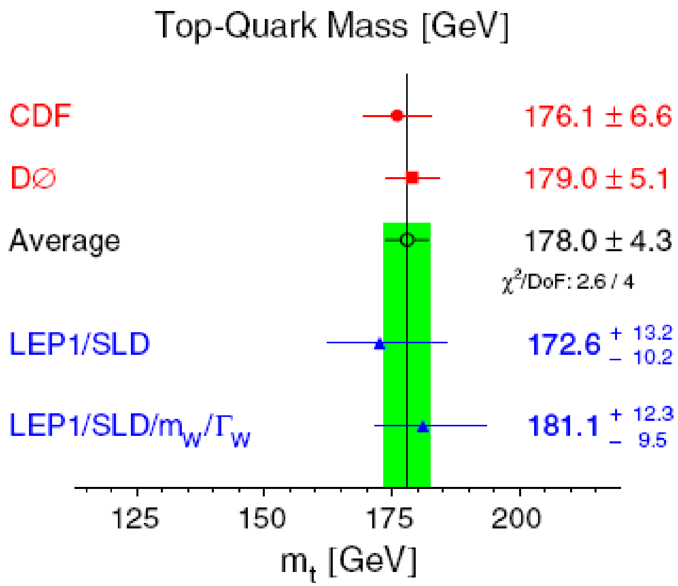
Mass of the Top Quark

indirect constrain

$$m_t = 173^{+13}_{-10} GeV$$

direct measurement

$$m_t = 178.0 \pm 4.3 GeV$$



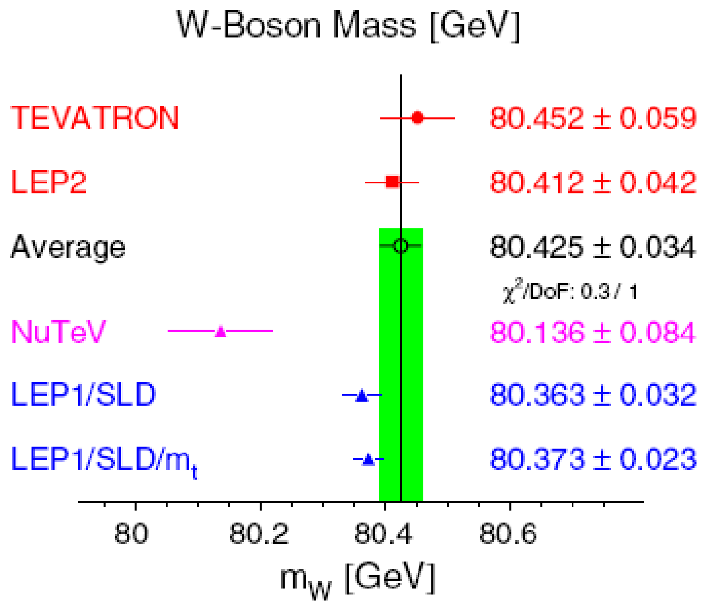
Mass of the W Boson

prediction

$$m_W = 80.363 \pm 0.032 GeV$$

direct measurement and prediction agree very well

Test of SM and its predictive power



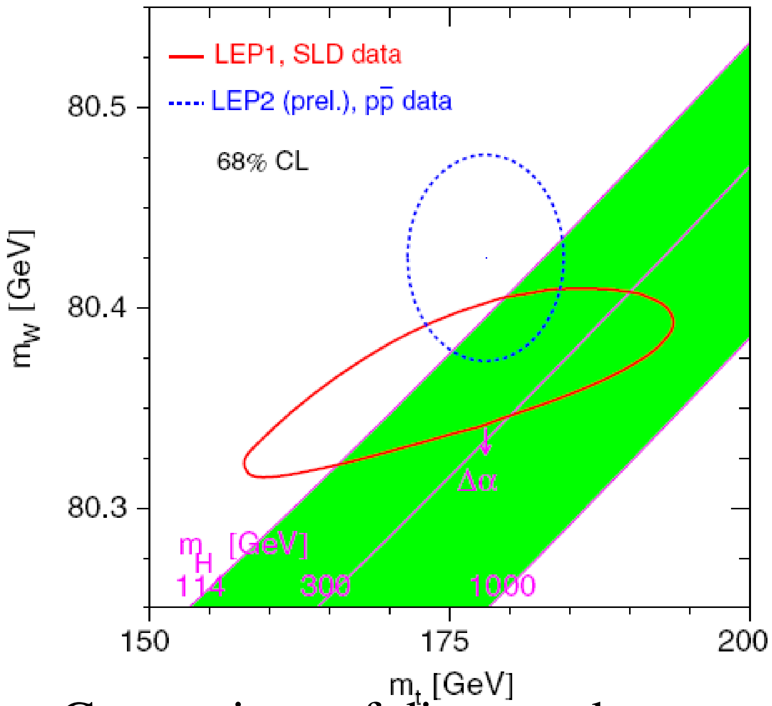
The Higgs boson

LEP II: 114.4 GeV < m_H

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

m_H < 285 GeV

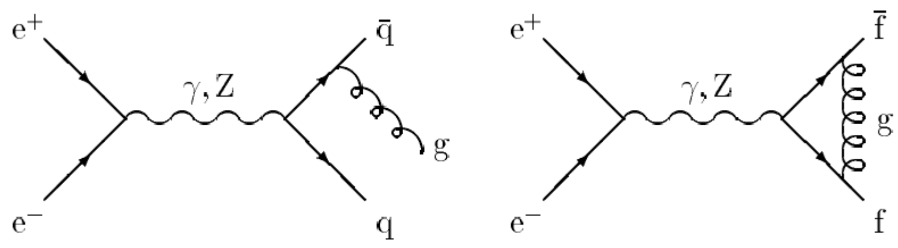
consistent with 95% confidence level



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 α_s

modification of hadronic cross section and decay width as a function of α_s

use to determine coupling

Determination of Strong Coupling Constant

ratio $$R_l = \frac{R_{had}}{R_{lep}} = 20.788 \pm 0.032$$

weak radiative corrections cancel

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

$$\alpha_s = 0.124 \pm 0.005 \pm 0.005$$

out of 3-jet events

$$\alpha_s(m_z) = 0.124 \pm 0.021$$

Summary

approximately 14 mio. Z decays

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

SM verified to be a good theory up to 100GeV

References

[1] "'Precision electroweak measurements on the Z resonance"', Physics Reports 427 (2006) 257-454

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

[3] Ralph Aßmann, "'Optimierung der transversalen Spin-Polarisation im LEP-Speichering und Anwendung für Präzsissionsmessungen am Z-Boson"'

[4] Ernest M Henley, Alejandro García, "'Subatomic Physics"', third edition

[5] Lecture on Advanced Particle Physics by Ulrich Uwer (2008)

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[7] OPAL Collaboration, "'The OPAL detector at LEP"', Nuclear Instruments and Methods in Physics Research A305 (1991) 275-319

[8] http://www.hep.phy.cam.ac.uk/ thomson/particles/questions/Q16$_answers.html$