ELEMENTARY PARTICLE PHYSICS
Current Topics in Particle Physics
Laurea Magistrale in Fisica, curriculum Fisica Nucleare e Subnucleare
Lecture 1

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Preliminaries

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Bibliography

- ♠ Bibliography
  - K.A. Olive et al. (Particle Data Group), *The Review of Particle Physics*, Chin. Phys. C, 38, 090001 (2014)(PDG) update 2015, http://pdg.lbl.gov/
  - F. Halzen and A. Martin, *Quarks and Leptons: An introductory course in Modern Particle Physics* , Wiley and Sons, USA(1984).

- ♠ Other basic bibliography:
  - A.Das and T.Ferbel, *Introduction to Nuclear Particle Physics* World Scientific,Singapore, 2^{nd} Edition(2009)(DF).
  - D. Griffiths, *Introduction to Elementary Particles* Wiley-VCH,Weinheim, 2^{nd} Edition(2008),(DG)
  - B.Povh *et al.*, *Particles and Nuclei* Springer Verlag, DE, 2^{nd} Edition(2004).(BP)
  - D.H. Perkins,*Introduction to High Energy Physics* Cambridge University Press, UK, 2^{nd} Edition(2000).
  - Y.Kirsh & Y. Ne'eman, *The Particle Hunters*

♠ Particle Detectors bibliography:

- William R. Leo *Techniques for Nuclear and Particle Physics Experiments*,
  Springer Verlag (1994)(LEO)
- C. Grupen, B. Shawartz *Particle Detectors*,
  Cambridge University Press (2008)(CS)
- *The Particle Detector Brief Book*,(BB)
  http://physics.web.cern.ch/Physics/ParticleDetector/Briefbook/

Specific bibliography is given in each lecture

Lecture Contents - 1 part

1. Introduction. Lep Legacy
2. Proton Structure
3. Hard interactions of quarks and gluons: Introduction to LHC Physics
4. Collider phenomenolgy
5. The machine LHC
6. Inelastic cros section pp
7. W and Z Physics at LHC
8. Top Physics: Inclusive and Differential cross section $t\bar{t}$ W, $t\bar{t}$ Z
9. Top Physics: quark top mass, single top production
10. Dark matter
    - Indirect searches
    - Direct searches

Specific Bibliography

♠ Bibliography of this Lecture

- ALEPH Collaboration, the DELPHI Collaboration, the L3 Collaboration, the OPAL Collaboration, the SLD Collaboration, the LEP Electroweak Working Group, the SLD electroweak, heavy flavour groups,
  Precision electroweak measurements on the Z resonance,
  CERN-PH-EP/2005-041, SLAC-R-774,
  arXiv:hep-ex/0509008,https://arxiv.org/abs/hep-ex/0509008
  Physics Reports. 2006, vol. 427, no. 5-6, p. 257-454
- J. Mnich,*Experimental Tests of the Standard Model in* $e^+e^- \to f\bar{f}$ *Z Resonance*, Phys. Rep. 271 (1996) 181

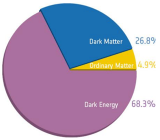
Contents

Introduction

The aim of the course is to provide students with a general overview of the current topics in experimental particle physics either accelerator either astroparticle quests. The aim is very ambitious and challenging for the lecturer and the students.

- The course will begin with an overview of LEP results.
- Introduction to LHC Physics.
  - Proton structure hard interactions of quarks and gluons (reminder)
  - Tool for this study will be shortly discussed as.Detector performances, identification of particles (e, μ,,) of jets, background subtraction techniques.
  - To prove to understand the well established physics is necessary before any claim any discovery.
  - Proton-proton collisions
    - For such purpose: W and Z Physics at LHC will be reviewed.
    - Top Physics: Inclusive and Differential cross section $t\bar{t}$ W, $t\bar{t}$ Z and quark top mass, single top production will be discussed.
    - The main discovery Higgs boson as already discussed in previous . I was asked not discuss.
  - Heavy Ions collisions

Introduction



- Dark matter: direct and indirect search. Antimatter at origin of Universe.
- Neutrino physics or High energy cosmic rays

Requested skills:

Fisica nucleare e subnucleare I e II, Meccanica quantistica.

- Seminars
- Laboratory
- Exams for attending to lectures and not attending students
- Introducing ourselves...

Contents

Lep legacy

The Large Electron Positron collider (LEP) gave a fundamental contribution to particle physics in particularly on the understanding of the Standard Model (SM) of the Electroweak (EW) and Strong (SI) Interactions .

LEP yielded a very large number of important experimental results (see the Particle Data Books) and has placed the SM on a solid experimental ground.

- He was housed in 27 km tunnel, actually used from the Large Hadron Collider(LHC)
- 4 experiments: ALEPH, DELPHI, L3 and OPAL
- LEP1: $\sqrt{s} \approx$ 91 GeV (1989 -1995)
- LEP2: $\sqrt{s} \approx$ 130-209 GeV (1995 -2000)
- LEP had luminosities of $10^{31} - 10^{32} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ which yielded collision rates of $\approx$1 event/s at LEP1 and $\approx$ 0.01 event/s at LEP2.

Physics e^+e^- colliders

• Weak mixing angle relates the masses of the heavy gauge bosons:

$$\cos\vartheta_{\mathrm{W}} = \frac{M_W}{M_Z}$$

• ρ parameter is the ratio of neutral to charged current coupling strength or equivalently boson mass relation:

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_{\mathrm{W}}}$$

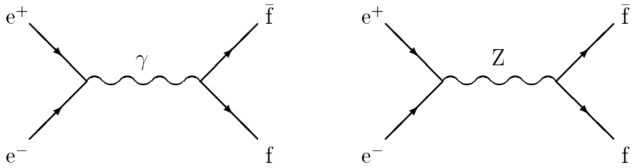
$\rho = 1$ in SM with one Higgs doublet.

• Deviation from $\rho = 1$ can originate from radiative corrections.

• The contribution of the vector and axialvector part to the interactions is different and their relative strength denoted by the vector and axialvector coupling constants g_V and g_A.

• In SM these coupling constants g_V, g_A are universal for all generations: Lepton Universality.

Electron positron annihilation



The cross section for massless fermions summing over all helicity states as function of θ scattering angle, between incoming electron e^- and outgoing fermion f can be written as m_Z:

$$\frac{d\sigma}{d\theta} = N_c^f \frac{\pi\alpha^2}{2s}\{Q_f^2(1 + \cos^2\theta) \qquad \gamma \text{ exchange}$$

$$-Q_f\left[2g_V^e g_V^f(1 + \cos^2\theta) + 4g_A^e g_A^f \cos\theta\right]\mathcal{R}\{\chi\} \qquad \text{Interference}$$

$$+\Big(\left[(g_V^e)^2 + (g_A^e)^2\right] + \left[(g_V^f)^2 + (g_A^f)^2\right](1 + \cos^2\theta)$$

$$+8g_V^e g_A^e g_V^f g_A^f \cos\theta|\chi|^2\} \qquad \text{Z exchange}$$

Electron positron annihlilation

$N_c^f = 1$ for leptons, $= 3$ for quarks

$$\chi = \frac{1}{4\sin^2\vartheta_{\mathrm{W}}\cos^2\vartheta_{\mathrm{W}}}\frac{s}{s - m_{\mathrm{Z}}^2 + i\Gamma_Z m_{\mathrm{Z}}}$$

Total width Γ_Z is the sum of the partial decay width into fermions Γ_f:

$$\Gamma_Z = \sum_f \Gamma_f$$

$$\Gamma_f = N_e^f \frac{\alpha m_{\mathrm{Z}}}{12\sin^2\vartheta_{\mathrm{W}}\cos^2\vartheta_{\mathrm{W}}}\left[(g_V^f)^2 + (g_A^f)^2\right]$$

Electron positron annihlilation: cross section

- The total cross section $e^+e^- \rightarrow f\bar{f}$ is :

$$\sigma_f = \frac{4\pi\alpha^2}{3s} N_c^f \{Q_f^2 - 2Q_f g_V^e g_V^f \mathcal{R}\{\chi\} + \left[(g_V^e)^2 + (g_A^e)^2\right] + \left[(g_V^f)^2 + (g_A^f)^2\right]|\chi|^2\}$$

For $\sqrt{s} = m_Z$ the interference term(second) vanishes and photon term(first) is very small.At Lowest Order (LO):

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

The peak cross section is thus the **product of the branching ratio of the Z decaying into initial an final state fermions** times a dimensional factor.

Electron positron annihlilation: cross section

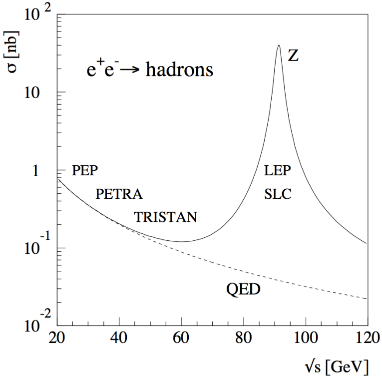


Figure : Lowest order cross section for $e^+e^- \to$ hadrons as function of center-of-mass- energy

The Br calculated from lowest order Γ_f(Eq.1)

Table : Lowest Br at Z

	$BR = \Gamma_f/\Gamma_Z$
e, μ, τ	3.5%
ν_e, ν_μ, ν_τ	7%
hadrons $\left(= \sum_q q\bar{q}\right)$	69%

About 20% of Z bosons decay into neutrinos and are not detected.

Electron positron annihlilation: asymmetry

- Straight forward derivation of other observables as :
  asymmetries $A_{FB} = \frac{N_F - N_B}{N_F + N_B}$
  F="forward" means that the produced fermion (as opposed to anti-fermion) is in the hemi-sphere defined by the direction of the electron beam (polar scattering angle $\theta < \pi/2$)

$$N_F = \int_0^1 \frac{\partial\sigma}{\partial\cos\theta} d\cos\theta \quad N_B = \int_{-1}^0 \frac{\partial\sigma}{\partial\cos\theta} d\cos\theta$$

Integrating Eq. 1 at $\sqrt{\mathrm{s}} = m_{\mathrm{Z}}$:

$$A^f_{FB}(s) = \frac{3}{8}\frac{-4Q_f g^e_A g^f_A \mathcal{R}\{\chi\} + 8 g^e_A g^e_V g^f_A g^f_V |\chi|^2}{Q^2_f - 2Q_f g^e_V g^e_f \mathcal{R}\{\chi\} + [(g^e_A)^2 + (g^e_V)^2][(g^f_A)^2 + (g^f_V)^2]|\chi|^2}$$

$$A^f_{FB}(\sqrt{\mathrm{s}} = m_{\mathrm{Z}}) = 3\frac{g^e_V g^e_A}{(g^e_V)^2 + (g^e_A)^2}\frac{g^f_V g^f_A}{(g^f_V)^2 + (g^f_A)^2}$$

Electron positron annihlilation: cross section

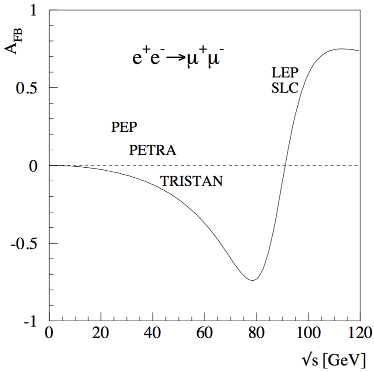


Figure : Lowest order forward-backward asymmetry for $e^+e^- \to \mu\mu$ as function of center-of-mass- energy

The cause of forward-backward asymmetry is the suporposition of vector and axial-vector currents.Thus, the interference of γ with axial component of Z gives rise to large asymmetry already at energies well below Z. At Z pole the axial and axial vector parts of Z determine the asymmetry. The relative strength of vector coupling of the Z to the charged leptons small and the observed asymmetry of $e^+e^- \to \mu\mu$ is small.

Radiative corrections- SM Parameters

The SM has several input parameters not predicted by the model that must be determined by experiment.A common used set of these **input parameters** :

$$\alpha, m_{\rm Z}, m_{\rm W}$$
$$m_H, \text{fermion masses}$$
$$\alpha_s, \text{CKM matrix}$$

The three parameter entering in the previous formula are : QED coupling constant $\alpha = \frac{e^2}{4\pi}$ and two vector boson masses. The weak mixing angle is defined with $\cos\vartheta_{\rm W} = \frac{M_W}{M_Z} \Longrightarrow$ all osservable of $e^+e^- \to f\bar{f}$ can be calculated in lowest order.
To incorporate mass effects and higher order diagrams in the calculations the masses of all fermions are required. Corrections to the massive gauge boson propagator depend from m_H. Cabbibo Kobayashi Maskawa (CKM) matrix relates the electroweak and mass eigenstates of quarks. All this parameter were well know except m_H.

All parameter were well known eccept m_H. In Standard Model calculations of electroweak observable were made with assumption of m_H at that time unknown.

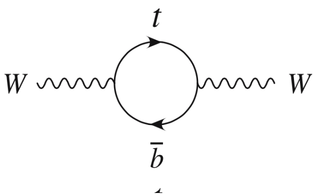
- QED coupling coupling constant was known was known with high precision
- m_Z is determined precisely by LEP
- m_W was known with relative precision of $\Delta m_W / m_W \sim 10{-}3$. So in the calculation was replaced from G_F, Fermi constant determined from μ lifetime
- the relation between m_W and G_F contains a term Δ_r describing the radiative corrections:

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2}\frac{1}{m_\mathrm{W}^2 \sin^2\theta_W}\frac{1}{1 - \Delta r}$$
$$\Delta r = \Delta\alpha_{QED} - \Delta r_w - \Delta r_{rem}$$

Δr_w weak radiative corrections, Δr_{rem} smaller.

Radiative corrections- Weak radiative corrections - top mass

The main cause of the weak radiative corrections Δr_w is the W vacuum polarization diagram, affecting m_{W} and m_{Z}. The contribution of this kind of diagrams is proportional to the **difference of the squared masses of the two fermions**.
Weak isospin symmetry breaking by fermion doublets with large mass splitting modifies the ρ parameter, which is unity in lowest order.



$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_w} \quad \text{(LO)}$$

$$\bar{\rho} = 1 + \Delta\rho$$

$$\Delta\rho_t = \frac{3G_F}{8\pi^2\sqrt{2}} \boldsymbol{m_t^2} + \text{.. is a quadratic dependence}$$

Radiative corrections- Weak radiative corrections - top mass

The weak radiative correction can be expressed as

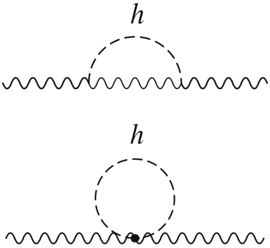
$$\Delta r_w = \frac{\cos^2 \theta_W}{\sin^2 \theta_W} \Delta \rho$$

The effect of the top quark mass is large and used at LEP to constrain m_t in SM.

Other weak interaction interesting:**virtual exchange of a Higgs boson.**

Radiative corrections- Weak radiative corrections -Higgs mass

Weak radiative corrections from virtual exchange of a Higgs boson. Since the **coupling of the Higgs is proportional to the mass of the particle** only diagrams where the Higgs couples to the heavy gauge bosons (W, Z) matter.



$$\Delta\rho_{\text{Higgs}} = \frac{3\sqrt{2}G_F m_{\text{W}}^2}{16\pi^2}\frac{\sin^2\vartheta_{\text{W}}}{\cos^2\vartheta_{\text{W}}}\left(\ln\frac{\boldsymbol{m_{\text{H}}^2}}{m_{\text{W}}^2} - \frac{5}{6}\right)$$

is a logarithmic dependence

To take in account radiative corrections the effective coupling constant $\bar{g}_A$ and $\bar{g}_V$ and weak mixing angle $\sin\bar{\theta}_W$, related to the lowest order, are introduced as:

$$\bar{g}_A^f = g_A^f\sqrt{\bar{\rho}_f} \qquad \bar{g}_V^f = g_A^f\sqrt{\bar{\rho}_f}(1 - 4|Q_f|\ \sin^2\bar{\theta}_W)$$

$$\sin^2\bar{\theta}_W^f = (1 + \frac{\cos^2\vartheta_\mathrm{W}}{\sin^2\vartheta_\mathrm{W}}\Delta\bar{\rho}_f + ...)\sin^2\vartheta_\mathrm{W}$$

The effective couplings are different for the fermions because of the flavor dependent corrections to the $Zf\bar{f}$ vertex resulting in slightly different $\bar{\rho_f} = 1 + \Delta\bar{\rho_f}$.The difference is small[1].The advantage of $\sin^2\bar{\theta}_W$ and effective coupling constants $\bar{g}_A^f\ \bar{g}_V^f$ are closely related to the observables at the Z resonance and Γ_f . Including radiative corrections can be written similarly at lowest order formula (Improved Born-approximation) replacing:

$$g_A, g_V \Longrightarrow \bar{g}_A^f\bar{g}_V^f \ \text{ corrisponds } \Gamma_f \text{ incl. radiative corrections}$$

$$\Gamma_f = N_e^f\frac{G_F m_\mathrm{Z}^3}{6\pi\sqrt{2}}\left[((\bar{g}_A^f)^2 + \bar{g}_V^f)^2\right] + \text{ QED and QCD corrections}$$

$$\Gamma_f + \text{ QED and QCD corrections}$$

[1]Except $Zb\bar{b}$.

Weak radiative corrections - QED correction- Remarks

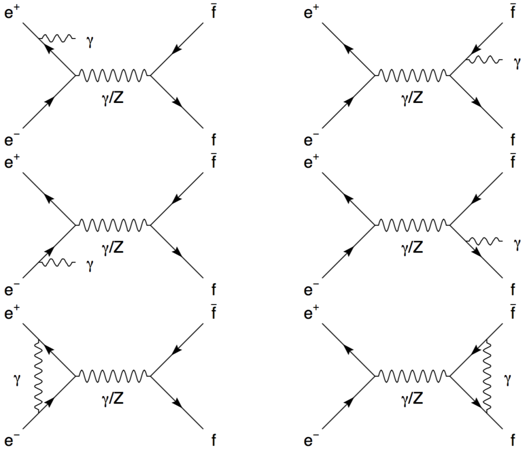
The interpretation of observables like Γ_ℓ or $\sin^2\bar{\theta}_W$ in terms of m_t or m_{H} implies the validity of the Standard Model.

- The QED correction in $\Delta\alpha$ arise from the running QED coupling constant α from its definition at low momentum transfer $(Q^2 \to 0)$ to the scale of the heavy gauge bosons:

$$\alpha m_{\mathrm{Z}} = \frac{\alpha}{1 - \Delta\alpha}$$

  Contribution to $\Delta\alpha$ for charged leptons are : 0.01743 (e^+e^-), 0.00918 $(\mu^+\mu^-)$,0.00481 $(\tau^+\tau^-)$,
- Other corrections due high order diagrams with additional real or virtual photons: initial, final state bremsstrahlung and correctio to $Zf\bar{f}$ vertex.
- initial, final state bremsstrahlung has huge impact on the cross section
- Qualitatively it can be understood considering the radiated photon as removing some fraction of the center-of-mass energy $\Longrightarrow$ $\sqrt{s} \to \sqrt{s'}$ where the cross section is different

QED corrections



Electron positron annihlilation: cross section

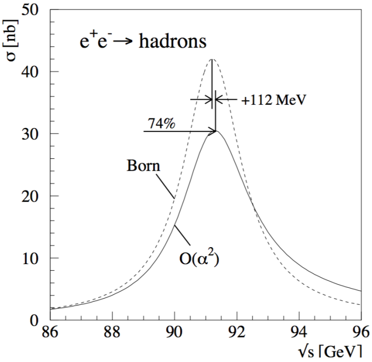
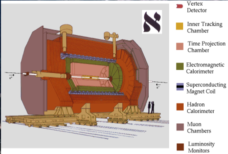


Figure : The cross section $e^+e^- \to$ hadrons including $\mathcal{O}(\alpha^\in)$ corrections(solid line) compared with LO cross section(broken line) at Z resonance.

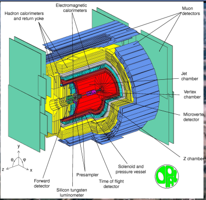
The High order QED diagrams led:

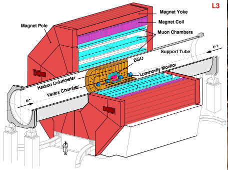
- a reduction of peak cross section 74%
- an energy shift of peak cross section by $\Delta(\sqrt{s}) = 112$ MeV
- and to an asymmetric cross section curve below and above Z pole.

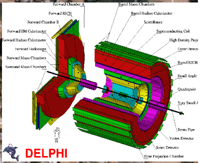
The Four LEP Detectors



The ALEPH Detector







Precision Electroweak Measurements on the Z Resonance

17 million Z decays accumulated

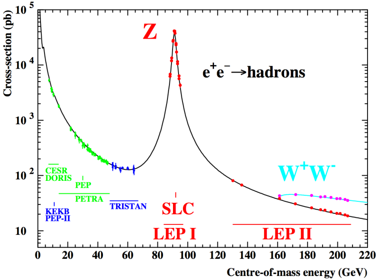
- $\boldsymbol{m_Z = 91.1875 \pm 0.0021}$ **GeV** $\Delta m_Z/m_Z = \pm 2.3 \cdot 10^{-5}$
- $\boldsymbol{\Gamma_Z = 2.4975 \pm 0.0023}$ **GeV**
- $\rho_\ell = 1.0050 \pm 0.0010$ GeV
- $\sin\theta_{eff}^{lept} = 0.23153 \pm 0.00016$
- **Number of light neutrino species: $\boldsymbol{2.9840 \pm 0.0082}$**
- Predict mass top: $m_t = 173^{+13}_{-10}$ GeV
- $\boldsymbol{m_W = 80.363 \pm 0.032}$ **GeV**
- Using direct measurements of m_t and m_W, the mass of the Standard Model Higgs boson is predicted with a relative uncertainty of about 50% and found to be less than 285 GeV at 95% confidence level.

Lep results

- ALEPH DELPHI L3 OPAL

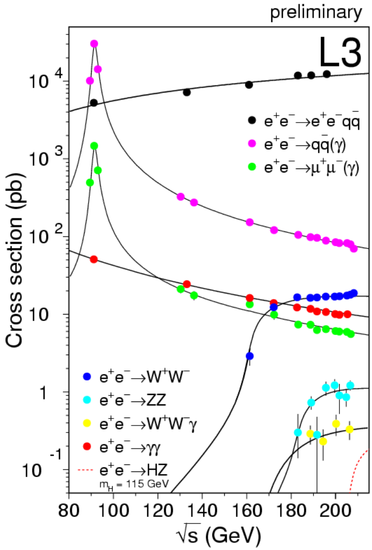
- LEP1: $\sqrt{s} \approx$ 91 GeV (1989 -1995): **Z boson physics**
- LEP2: $\sqrt{s} \approx$ 130-209 GeV (1995 -2000):**W boson physics, search for new particle & phenomena**
- LEP had luminosities of $10^{31} - 10^{32} cm^{-2} s^{-1}$ which yielded collision rates of $\approx$1 event/s at LEP1 and $\approx$ 0.01 event/s at LEP2.
- Precise beam energy calibration: $< \pm 1$ MeV(LEP I) $\sim \pm 15$ MeV (LEP II)

Hadron cross section



The hadronic cross-section as a function of centre-of-mass energy. The solid line is the prediction of the SM, and the points are the experimental measurements. Also indicated are the energy ranges of various e^+e^- accelerators. The cross-sections have been corrected for the effects of photon radiation.

The Legacy of LEP



The LEP main achivements:

- The SM has been demonstrated correct
  - up 209 GeV
  - and beyond the tree level
- Many high precision measurements
  - e.g. cross sections
- No Higgs boson observed
  - direct search $e^+e^- \to HZ$ $m_{\mathrm{H}} > 114.4$ GeV
- NO new phenomena observed

Z lineshape

• The behaviour of the cross-section around the Z peak is typical of a resonant state with J=1, and is well described by a relativistic Breit-Wigner formula plus electromagnetic and interference terms.

• The formula has to be convoluted with initial state radiation.Around the Z, the last 2 terms are small corrections to the main Z Breit-Wigner term.

• The formula depends on m_Z and on the partial width for the Z decay into a fermion-antifermion pair.

$$\sigma_f^Z = \sigma_f^{peak} \frac{s\Gamma_Z^2}{(s - m_Z^2)^2 + s^2\Gamma_Z^2 m_Z^2}$$

where $\sigma_f^{peak} = \frac{1}{R_{QED}}\sigma_f^0$ and $\sigma_f^0(\sqrt{s} = m_Z) = \frac{12\pi}{m_Z^2}\frac{\Gamma_e\Gamma_{f\bar{f}}}{\Gamma_Z^2}$

The term $\frac{1}{R_{QED}}$ removes the final state QED correction included in the definition of Γ_{ee}.

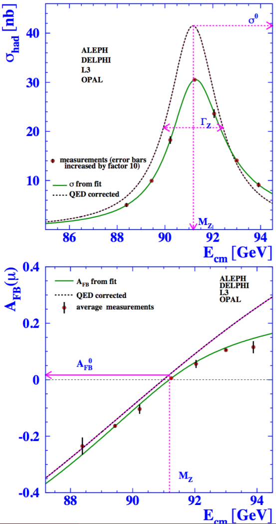
Z lineshape

- Hadronic cross-sections

$$\sigma^0_{\rm had}(\sqrt{s} = m_Z) \approx \frac{12\pi}{m_Z^2}\frac{\Gamma_e\Gamma_{\rm had}}{\Gamma_Z^2}$$
$$\Gamma_{\rm had} = \sum_{q\neq t}\Gamma_{q\bar{q}}$$

- The muon forward-backward asymmetry

The full line represents the results of model-independent fits to the measurements, correcting for QED photonic effects yields the dashed curves, which define the Z.



Number of Neutrino families

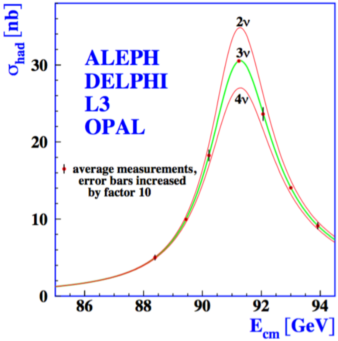
• The invisible partial width, Γ_{inv}, is determined by subtracting the measured visible partial widths, corresponding to Z decays into quarks and charged leptons, from the total Z width. The invisible width is assumed to be due to N_ν light neutrino species each contributing the neutrino partial width Γ_ν as given by the Standard Model.

$$\Gamma_Z = \Gamma_e + \Gamma_\mu + \Gamma_\tau + \Gamma_{\text{had}} + \Gamma_{\text{inv}}$$
$$\Gamma_{\text{inv}} = \boldsymbol{N_\nu} \Gamma_\nu$$

In order to reduce the model dependence, the Standard Model value for the ratio of the neutrino to charged leptonic partial widths, $\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\text{SM}} = 1.991 \pm 0.001$ is used instead of $\left(\Gamma_\nu\right)_{\text{SM}}$ to determine the number of light neutrino types:

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_\ell} \left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\text{SM}}$$

Number of Neutrino families



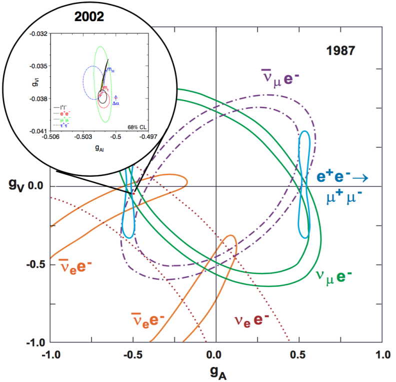
$$N_\nu = 2.9840 \pm 0.0082$$

Still on PDG

Comparison with SM

- **These observed properties are found to be in good agreement with expectations of the SM.** We first focus on comparing the Z-pole data with the most fundamental SM expectations (lepton universality, consistency between the various manifestations of $\sin\vartheta_W^2$, etc.).
- Let assume the validity of the SM, and **perform fits which respect all the inter-relationships among the measurable quantities**which it imposes.
- These fits find optimum **values of the SM parameters**, and determine whether these parameters can adequately **describe the entire set of measurements simultaneously**.
- Improved knowledge of the properties of the Z, in addition to the precise measurements of its mass, width and pole production cross-section, is g_A, g_V.
- The good agreement between the top quark mass measured directly at the Tevatron and the predicted mass determined indirectly within the SM framework from the measurements at the Z-pole,.

Coupling constant



- The neutrino scattering and e^+e^- data (1987) constrained the values of $g_{V\ell}$ and $g_{A\ell}$. The intersections helped establish the validity of the SM and were consistent with the hypothesis of lepton universality.
- In inset the results of the LEP/SLD measurements (scale x 65) .
- The flavour-specific measurements $\Longrightarrow$ the **universality of the lepton couplings** unambiguously on a scale of approximately **0.001**.

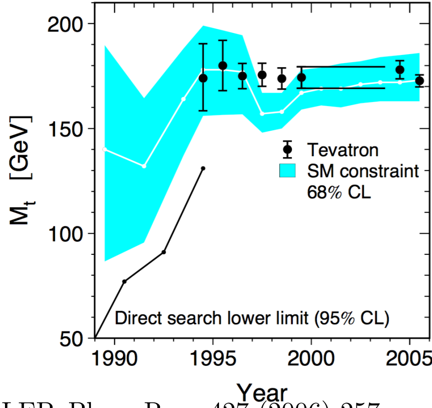
Top mass

- Analysis of radiative corrections within the framework of the SM using precision electroweak measurements (68%C.L.) shaded area.

$$\Delta\rho_t = \frac{3G_F}{8\pi^2\sqrt{2}} \boldsymbol{m_t^2}$$

- Direct measurements of m_t at Tevatron(CDF D0) (error bars 68%C.L.)
  $\boldsymbol{m_t = 174.34 \pm 0.64}$ **GeV**
- From precision Z osservable
  $\boldsymbol{m_t = 173^{+13}_{-10}}$ **GeV**

Direct and indirect determinations of the mass of the top quark, m_t, as a function of time.



LEP, Phys. Rep. 427 (2006) 257

PDG 2015 : $\boldsymbol{m_t = 173.21 \pm 0.51 \pm 0.71}$ **GeV**

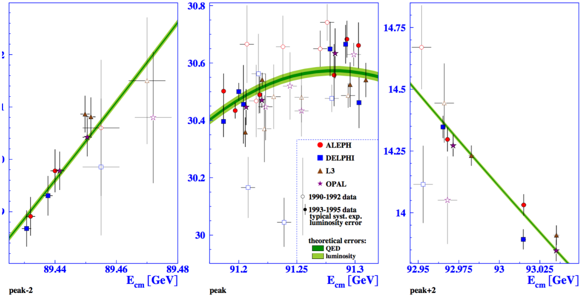
Z lineshape and Forward and backward asymmetries: achievements

♣ The main aim was determine the essential parameters of the Z resonance, its mass, its width, its branching fractions, and the angular distribution of its decay products.Specifically $m_{\mathrm{Z}}, \Gamma_Z, \sigma^0_{\mathrm{had}}, R^0_\ell \equiv \frac{\Gamma_\ell}{\Gamma_{had}}, A^{0,\ell}_{\mathrm{FB}}$ for each lepton species.

- The mass of the Z is a central parameter of the Standard Model (SM): m_{Z} know with $\Delta m_{\mathrm{Z}}/m_{\mathrm{Z}} = \pm 2.3 \cdot 10^{-5}$.
- Γ_Z is of similar importance: the width of the Z to each of its decay channels is proportional to the fundamental Z-fermion couplings.
- The spin-1 nature of the Z is well substantiated by the observed $(1 + \cos^2\theta)$ angular distribution of its decay products.The $\cos\theta$ terms of the angular decay distributions, varying as a function of energy due to Γ_Z interference, determine the three leptonic pole forward-backward asymmetries, $A^{0,\ell}_{\mathrm{FB}}$

Other precision measurements have been performed as τ decay properties, heavy and light quarks asymmetries, charmed mesons, hadrons .....

Z cross section



Measurements by the four experiments of the hadronic cross-sections around the three principal energies. The vertical error bars show the statistical errors only. The open symbols represent the early measurements with typically much larger systematic errors than the later ones, shown as full symbols.

Asymmetries

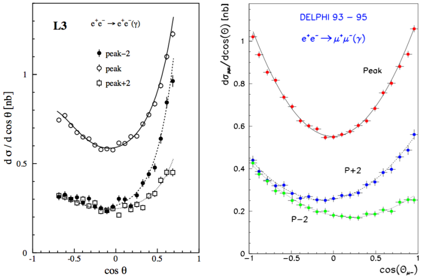
•The forward-backward asymmetry, A_{FB}, is defined by the numbers of events, N_F and N_B, in which the final state lepton goes forward ($\cos\theta_\ell^- > 0$) or backward ($\cos\theta_\ell^- < 0$) with respect to the direction of the incoming electron, $A_{FB} = (N_F - N_B)/(N_F + N_B)$. This definition of A_{FB} depends implicitly on the acceptance cuts applied on the production polar angle, $\cos\theta$, of the leptons.

• The measurements of $A_{FB}(\ell^+\ell^-)$ require the determination of $\cos\theta$ and the separation of leptons and anti-leptons based on their electric charges, which are determined from the curvature of the tracks in the magnetic fields of the central detectors.

• For $\mu^+\mu^-$ and $\tau^+\tau^-$ final states, A_{FB} is actually determined from fits to the differential cross-section distributions of the form $\mathrm{d}\sigma/\mathrm{d}\cos\theta \ \propto \ 1 \ + \ \cos^2\theta \ + \ 8/3 \cdot \mathrm{A_{FB}} \cos\theta$.

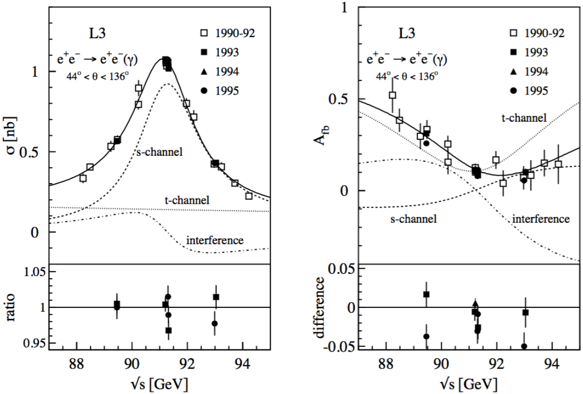
• The shape of the differential cross-section in the electron final state is more complex due to contributions from the t-channel and the s-t-interference, which lead to a large number of events in which the electron is scattered in the forward direction.

Polar angle



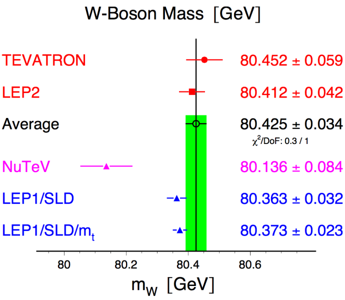
Distribution of the production polar angle, $\cos\theta$, for e^+e^- and $\mu^+\mu^-$ events at the three principal energies during the years 1993-1995. The curves show the SM prediction.

s-channel t-channel



Contributions from the s and t-channel diagrams and from the s-t interference for observables in the e^+e^- channel. Total cross-section (left) and the difference between the forward and backward cross-sections after normalisation to the total cross-section (right). The data points measured in an angular acceptance of $|\cos\theta| < 0.72$,a minimum electron energy of > 1 GeV. Lines are model independent fit.

W boson mass



The W boson mass have not been measured with same precison of Z. At present(PDG2015):

$$m_W = 80.385 \pm 0.015 \text{ GeV}$$

The most stringent constraint on the mass of the SM Higgs boson, the analysis is performed using the 14 Z-pole results, as well as the three additional results m_t, m_W and Γ_W, for a total of 18 input measurements.

- Fit 9 parameter: $m_\mathrm{Z}, \Gamma_Z, \sigma_0^\mathrm{had}, R_e^0, R_\mu^0, R_\tau^0, A_\mathrm{FB}^{0,e}, A_\mathrm{FB}^{0,\mu}, A_\mathrm{FB}^{0,\tau}$
- Imposing **lepton universality**:
  Fit 5 parameter $\boldsymbol{m_\mathrm{Z}, \Gamma_Z, \sigma^0_\mathrm{had}, R^0_\ell, A^{0,\ell}_\mathrm{FB}}$

reminder: $A_{FB} = (N_F - N_B)/(N_F + N_B)$ and $R^0_\ell \equiv \frac{\Gamma_{had}}{\Gamma_{\ell\ell}}$

Global fit Higgs mass

$$\Delta\rho_{\text{Higgs}} = \frac{3\sqrt{2}G_F m_{\text{W}}^2}{16\pi^2}\frac{\sin^2\vartheta_{\text{W}}}{\cos^2\vartheta_{\text{W}}}\left(\ln\frac{\boldsymbol{m}_{\mathbf{H}}^2}{m_{\text{W}}^2} - \frac{5}{6}\right)$$

- From Radiative corrections
  $m_{\text{H}} < 285$ GeV
- From Direct measurement
  $m_{\text{H}} > 114.4 \pm 0.64$ GeV
- Discovered
  $m_{\text{H}} = 125.09 \pm 240$ MeV

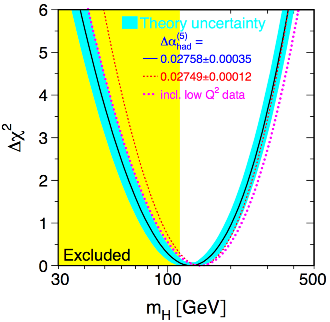
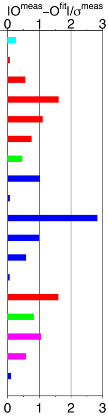


Figure : The associated band represents the estimate of the theoretical uncertainty due to missing higher-order corrections. Vertical band direct search $m_{\text{H}} > 114.4$ GeV.

SM observable

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^{0} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5



- Comparison of the measurements with the expectation of the SM, calculated for the five SM input parameter values in the minimum of the global χ^2 of the fit.
- Also shown is the pull of each measurement, where pull is defined as the difference of measurement and expectation in units of the measurement uncertainty. (The direct preliminary measurements of m_W and Γ_W)

Conclusion

♠ I had to miss the discussion of a lot of precision measurements: τ polarization, light and heavy quark production and asymmetries..

♠ An enormous number of searches of new physics: SUSY and MSSM Higgs and exotics particles have been carried on. These have been superseded by LHC results, no interest anymore except for methodology.

♠ A lot of statistical tools and search methodology have been invented in LEP experiment and the applied at LHC.

- **LEP experiments established the validity of SM**
- **Predicted m_t accuratly**
- **Predicted a range for m_{H}**
- No new physics observed (SUSY, extradimension...)
- LHC completed the triumph of SM.