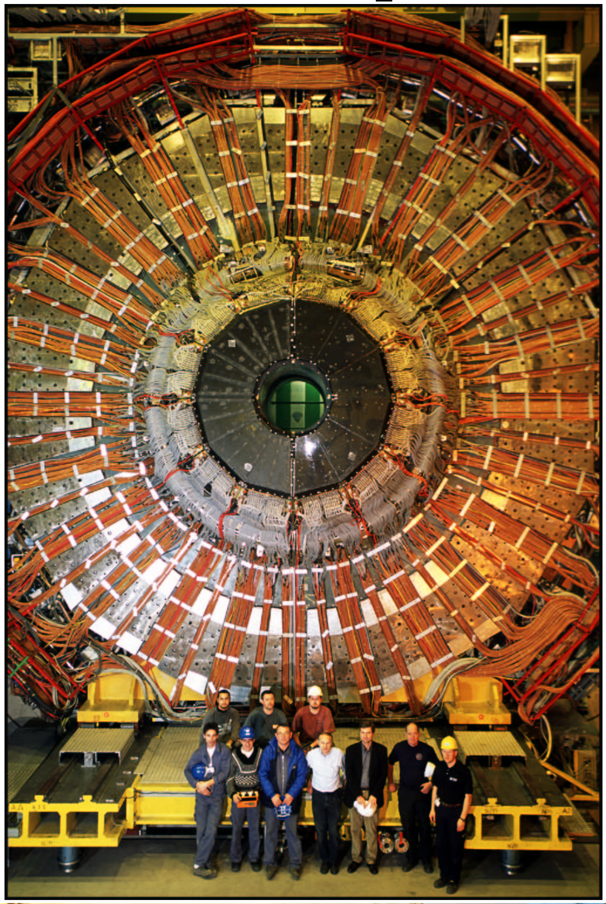
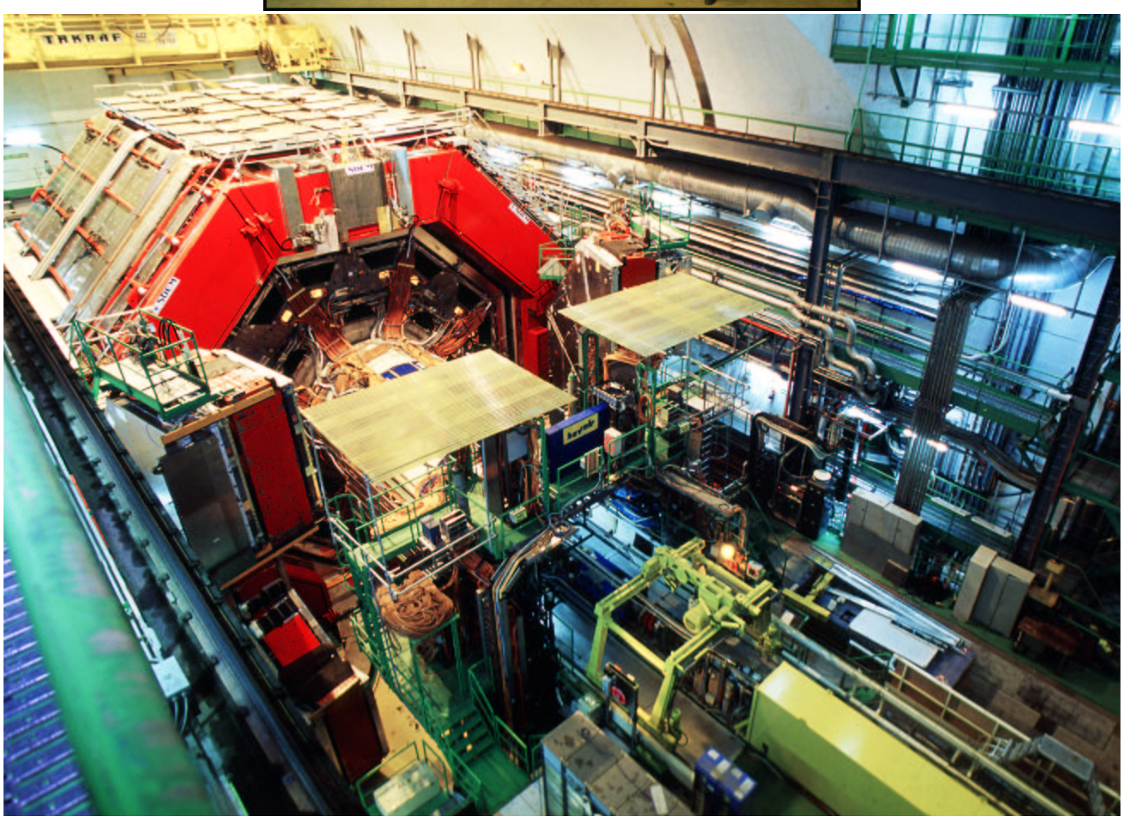
FOM-programme LEP (CERN)
Final Report





Frontpage figure: The (top) DELPHI and (bottom) L3 detectors.

FOM-programma LEP (CERN) Eindrapport

P. Kluit and W.J. Metzger

Samenvatting

Although 't Hooft and Veltman did their—now prize-endowed—work around 1970, it has taken a long time for us to understand the extent of their ground-breaking efforts. We had to wait for the results from an accelerator called the Large Electron Positron (LEP) at the European Laboratory for Particle Physics (CERN) ... This accelerator, inaugurated in 1989, ... has set the world record in precision measurements of electroweak interactions. 't Hooft and Veltman's work has been a prerequisite for interpreting these results.[1]

Van 1989 tot en met het jaar 2000 hebben vier detectoren op CERN gegevens verzameld over e^+e^- interacties die door de grote elektron positron botser, LEP , werden geproduceerd. Twee van deze experimenten DELPHI en L3 hebben bij dit onderzoek FOM steun ontvangen. Belangrijke componenten van deze twee detectoren en ook computer software zijn door NIKHEF medewerkers ontwikkeld en gebouwd.

In de eerste fase van LEP , tot de zomer van 1995, werd er zwaartepuntsenergieën gekozen rondom de massa van het Z-boson, om zodoende zijn eigenschappen met grote nauwkeurigheid te kunnen bestuderen. Later werd de zwaartepuntsenergie stapsgewijs verhoogd voor een studie van de $W^\pm$ bosonen, die in paren worden geproduceerd, en om te zoeken naar het Higgs boson en naar andere nieuwe deeltjes.

De precisie van de metingen van de eigenschapen van het Z deeltje hebben alle verwachtingen overtroffen. De bepaling van de Z-massa is het nauwkeurigst, met een preciesie van 23 ppm. Door de vele nauwkeurige metingen van de Z en W eigenschappen kan de elektrozwakke theorie in groot detail getoests worden. Een groot succes was de voorspelling van de massa van het top-quark voordat dit quark werd ontdekt. Deze massa geeft een bijdrage aan de eigenschappen van het Z-boson via quantumcorrecties.

Op analoge manier wordt een bovengrens gesteld ($< 219, \mathrm{GeV}$) op de massa van het Higgs boson. Door verder rechtstreeks naar het Higgs boson te zoeken (en het niet te vinden) wordt een ondergrens op de de massa van 114.4GeV bepaald. Het Higgs boson is het enige tot nu toe onontdekte deeltje uit de elektrozwakke theorie.

Ontwikkeling en installatie van silicium microvertex detectoren hebben belangrijke metingen van de eigenschappen van B mesonen en het τ-lepton mogelijk gemaakt, onderzoeksgebieden die bij de start van LEP niet waren voorzien.

Quantum ChromoDynamica (QCD), de component van het standaardmodel dat de sterke wisselwerking beschrijft is eveneens uitvoerig getoetst bij LEP . Omdat er geen hadronen in de

[1]Prof. Cecilia Jarlskog, Presentation speech for the 1999 Nobel Prize in Physics

in-toestand voorkomen. Voorziet LEP in een zeer schone omgeving voor het bestuderen van QCD. De sterke koppelinsconstante is gemeten en vertoonde een variatie met de energieschaal, precies zoals door QCD wordt voorspeld. De kleur structuur van de eindtoestand was eveneens in overeenstemming met de theorie.

Ondanks intensief zoeken naar deeltjes en verschijnselen die buiten de context van het standaard model vallen zijn deze niet waargenomen.

Promovendi en stafleden uit de wetenschappelijke en technische afdelingen hebben bijgedragen aan alle aspecten van de experimenten. Tot van daag zijn 49 proefschriften met succes verdedigd aan Nederlandse universiteiten gebaseerd op de LEP resultaten, er worden er nog 5 verwacht in de nabije toekomst. Het totaal aantal publicaties in wetenschappelijke tijdschriften is ongeveer 300 per experiment.

FOM-programme LEP (CERN) Final Report

P. Kluit and W.J. Metzger

Summary

> *Although 't Hooft and Veltman did their—now prize-endowed—work around 1970, it has taken a long time for us to understand the extent of their ground-breaking efforts. We had to wait for the results from an accelerator called the Large Electron Positron (LEP) at the European Laboratory for Particle Physics (CERN) ... This accelerator, inaugurated in 1989, ... has set the world record in precision measurements of electroweak interactions. 't Hooft and Veltman's work has been a prerequisite for interpreting these results.*[2]

From 1989 through 2000, four detectors at CERN collected data on e^+e^- interactions produced by the large electron-positron collider, LEP. Two of these experiments, DELPHI and L3, were supported by FOM. Important components of both detectors, as well as computer software, were developed and built by NIKHEF.

In the first phase of operation, up to mid-1995, the centre-of-mass energy was chosen approximately equal to the mass of the Z boson in order to study its properties with high precision. Later, the centre-of-mass energy was increased in steps to allow study of the $W^\pm$ bosons, which were produced in pairs, and to search for the Higgs boson and for new types of particles.

The precision of the measurements of Z properties surpassed all expectations. Most precise is the measurement of the mass of the Z, which has a precision of 23 ppm. From the many, precise measurements of Z and W properties, the theory of electroweak interactions could be tested in great detail. A major success was the prediction, before its discovery, of the mass of the top quark, which enters the calculation of Z properties as a small electroweak loop correction. Similarly, an upper limit ($< 219\,\mathrm{GeV}$) is placed on the mass of the Higgs boson. A direct search for the Higgs boson established the lower limit, $M_\mathrm{H} > 114.4\,\mathrm{GeV}$. The Higgs boson is the only particle of the electroweak theory which has not yet been discovered.

Development and installation of silicon microvertex detectors enabled significant measurements of properties of B-mesons and the tau lepton, areas of research not foreseen at the start of the LEP programme.

Quantum Chromo-Dynamics (QCD), the other component of the Standard Model, was also tested at LEP, the lack of hadrons in the initial state providing a very clean environment for QCD studies. The strong coupling constant was measured and found to depend on the energy scale as predicted by QCD. The colour structure of the final state was also found to be in accordance with the theory.

[2]Prof. Cecilia Jarlskog, Presentation speech for the 1999 Nobel Prize in Physics

Despite intensive searches, evidence for particles or processes beyond the Standard Model was not found. The LEP data are consistent with the Standard Model.

Ph.D. students and staff took part in all aspects of the experiments. To date, 49 Dutch Ph.D. theses have been based on LEP results, and 5 more are expected in the near future. The total number of articles in leading scientific journals will be about 300 per experiment.

Contents

Samenvatting **iii**

Summary **v**

1 Introduction **1**

2 The Detectors **3**

3 The LEP-I physics programme **6**
3.1 Electroweak measurements 6
3.2 QCD 11
3.3 Heavy Flavour physics 14

4 The LEP-II physics programme **18**
4.1 W physics 19
4.2 Higgs and new particle searches 22
4.3 QCD 24

5 Cosmic ray muons **26**

6 Conclusions: FOM LEP programme **28**

7 Conclusions: Outlook **29**

A Ph.D. Theses in The Netherlands **30**

B Publications **33**

Chapter 1

Introduction

Although the FOM programme "LEP," of which this is the final report commenced in 1997, the actual participation of FOM in the LEP programme at CERN started much earlier. The date 1997 reflects merely a change of administrative procedure at FOM toward "programme financing." To obtain a good picture of the achievements of LEP, this report will cover the entire LEP period.

In May 1977 the European Committee on Future Accelerators (ECFA), expressing wide consensus among European physicists, recommended a large electron-positron storage ring facility (LEP) as Europe's next major high-energy physics facility. Design began, approval of the machine followed in 1981, and construction began in 1983. First beams were delivered to the experiments in 1989. In its first phase, known as LEP-I (1989–1995), LEP ran with a centre-of-mass energy, $\sqrt{s}$, approximately equal to the mass of the Z boson. Midway in 1995, LEP entered its second phase, LEP-II, during which the energy was increased in steps to a maximum of 209 GeV in 2000, the last year of LEP operation.

Let us recall briefly the situation in 1977 to see why LEP was such an attractive machine. The Glashow-Weinberg-Salam theory uniting electromagnetic and weak interactions had been proposed. It required two new gauge bosons the Z^0 and $W^{\pm}$ particles. These particles were discovered in 1983 at the CERN $p\bar{p}$ collider. Some properties of the Z^0 and $W^{\pm}$ bosons were measured, but the statistics was too low to provide a precision test of the electroweak theory. LEP was designed to perform precision tests of the electroweak theory and also of the candidate theory of strong interactions, QCD. Some features of QCD would be tested before the start of LEP, in particular the existence of the gluon, the carrier of the strong force, which was established by the discovery of three-jet events at PETRA. Together, the electroweak theory and QCD comprise the Standard Model. The Standard Model also predicted the existence of a partner of the bottom quark, the top quark, as well as the Higgs boson, responsible for the mass of the particles. Further, it was possible to incorporate more than three families of particles (new quarks and leptons) in the Standard Model. Note further that the theory we now call the Standard Model was not unchallenged; a whole spectrum of alternative theories existed.

Thus LEP was envisaged to perform precision measurements of the parameters, and hence precise tests, of the electroweak theory. It would also provide tests of QCD beyond those possible at the then available, lower energy e^+e^- colliders PETRA and PEP. The first objective was to be realised by a machine whose centre-of-mass energy could be set equal to that of the Z mass (LEP-I), which would provide copious production of the Z boson, as well as to an energy significantly greater than twice the mass of the W (LEP-II) in order to produce W^+W^- pairs. This high energy and wide energy range would facilitate the further testing of QCD,

as well as searches for the top quark, the Higgs boson, and other new particles. LEP was expected to answer questions such as: What is the number of neutrino families? What are the masses of the W and Z bosons? What are the basic couplings of the fermions (quarks and leptons) to the gauge bosons? Do the gauge bosons couple to each other in the way the Standard Model predicts? What is the value of the strong coupling constant and does it run as a function of the energy as predicted by QCD? LEP would also be an ideal environment to search for the unexpected; new particles could be cleanly reconstructed and their properties could be precisely measured.

It was hoped that the top quark would be discovered at LEP, if not already discovered at PETRA. However, the mass of this quark would prove to be too high. The capability of the LEP detectors to study precisely b-quark and τ-lepton properties was not foreseen. However, due to the introduction of high precision silicon tracking detectors close to the beam pipe, these particles could be tagged (by reconstructing their decay vertex) and studied in great detail.

In Chapter 2, a brief summary is given of the Dutch components of the DELPHI and L3 detectors. This is followed in Chapters 3 and 4 by a summary of the most important physics results of the LEP-I and LEP-II programmes. The L3 cosmic ray results are briefly described in Chapter 5. Finally, conclusions regarding the FOM LEP programme and an outlook are given.

Chapter 2

The Detectors

FOM participated from their beginning in two of the four LEP experiments, DELPHI and L3, which were approved by CERN in 1982. While all four detectors can be called "general purpose," they are not identical. Compromises must be made in the design of the detectors, and DELPHI and L3 chose to emphasize different aspects. DELPHI chose a large TPC tracking detector and a silicon microvertex detector in a 1.2 T magnetic field and RICH detectors to identify the types of charged particles. L3, on the other hand, chose to emphasize lepton and photon measurements, by using a small tracking detector in a 0.5 T field in conjunction with good calorimetry, in particular the electromagnetic calorimeter consisting of BGO ($Bi_4Ge_3O_{12}$) crystals, and large muon detectors within the magnet.

Major NIKHEF contributions to the initial detectors:

DELPHI

- Barrel RICH
  - Technical support at CERN for construction of drift tubes
  - Construction external cylinder
  - Construction of 24 (+spares) readout wire chambers
  - Contribution to the general infrastructure for the detector
- Forward RICH
  - Construction liquid radiator
  - Contribution to the general infrastructure for the detector
- Inner Detector
  - Design of both parts of detector: Jet Chamber and Trigger Layers
  - Construction of complete Jet Chamber
  - Construction of inner cylinder and end flanges Trigger Layers
  - Design and construction of analogue readout electronics for both detector parts
  - Design and construction of (digital) trigger electronics for both detector parts
  - Design and construction of low- and high-voltage distribution systems
  - Development online monitoring software
  - Development offline track reconstruction software
- UV laser system

  - Design and construction of 12 (+spares) UV laser modules and control system. These laser beams were used in common for the Time Projection Chamber and the Jet Chamber for detector calibration.

L3

- Muon chambers
  - Prototypes and design of the muon system
  - Production of the 32 of the 80 large drift chambers, namely the 32 middle ones
  - Design, calibration and production of the opto-mechanical horizontal and vertical alignment systems
  - Calibration and monitoring of the magnetic field.
  - Development of offline track reconstruction software
  - Electronics
    - ⋆ Design and production of the 24,000 channel muon chamber front-end electronics
    - ⋆ 5 of the 10 VME-based monitor and control systems for the muon chambers:
      - · the opto-mechanical alignment system consisting of 304 sub-systems of a four-quadrant diode, a lens, and a LED, each with its amplifiers, multiplexers and control (NIKHEF);
      - · the UV laser control system (NIKHEF + Nijmegen);
      - · the time-zero calibration for the 48,000 measuring wires (NIKHEF);
      - · the control of the discriminator crates and thresholds (Nijmegen);
      - · the 928 magnetic field probes mounted on the muon chambers to monitor the field in the regions of the magnet where muons are measured (Nijmegen).
    - ⋆ Production of the level-4 BGO readout and associated software (Nijmegen).
- BGO: As part of a study to examine the correlations between the parameters of the BGO crystal growth and the properties of the ensuing BGO crystals, a project in Nijmegen grew about 100 large (L3-size) crystals.
- Software
  - Development of event display software.
  - Development of Monte Carlo event simulation programs.

In the course of LEP running, the need for various upgrades became apparent. NIKHEF contributed the following:

DELPHI

- Forward Tracking Chamber A
  - Construction of second generation detector drift tubes
- Inner Detector
  - Design and construction of a new, longer version of the Jet Chamber, for increased track acceptance in the forward/backward direction at LEP2. This detector was operational from 1995 onwards.

- Contribution to readout electronics of new Jet Chamber and new, longer version of the Trigger Layers (straw tubes detector)

L3

- Luminosity detector upgrade to improve its geometrical acceptance and granularity:
  - silicon-PC-board design, mechanical design, and assembly (NIKHEF)
  - VME-DAQ and VME-VAX communications (Nijmegen)
- Silicon Microvertex Detector was added to improve b-quark and tau-lepton identification and measurement. The mechanical support system and manipulator to install the silicon ladders, cooling and electronics were built at NIKHEF. This required very high mechanical precision. The experience gained would be of great use in the design and construction of the ZEUS and ATLAS vertex dectors.
- Forward muon chambers were added to enable muon detection in the forward region. The electronics, 20000 channels, was developed and produced at NIKHEF, as well as specialized tools for the installation and the RASNIK alignment system.
- L3+C: The read-out of the barrel muon system was upgraded to allow parallel readout of the muon chambers between LEP beam-crossings. This enabled the muon chambers to be used for the detection of muons produced by cosmic rays. The electronics were built by NIKHEF and Nijmegen:
  - 250 CPC cards (96 channel TDC cards)
  - 16 NIMROD VME modules to read out and control the CPCs
  - a JTAG buffer/fan-out module
  - 2 CTT (Clock Timing Trigger) modules

The L3 detector is shown on the cover of this report. Scintillator sheets, which provide a trigger for the cosmic-muon events are mounted on the top of the detector. A cross section of the endcap of the DELPHI detector, allowing a look into the calorimeter and muon systems, also appears on the cover.

To facilitate communication among members of the LEP collaborations, spread throughout the world, CERN, starting in 1989, developed the World-Wide Web. One of the first laboratories outside CERN to take part in the development was NIKHEF.

High speed networking, pioneered in The Netherlands by NIKHEF, was essential to allowing physicists not stationed in CERN to actively participate in the experiments. An example is the Monte Carlo event simulation farm consisting of about 30 computers in Nijmegen, which at its peak accounted for about 25% of L3's simulation.

Chapter 3

The LEP-I physics programme

3.1 Electroweak measurements

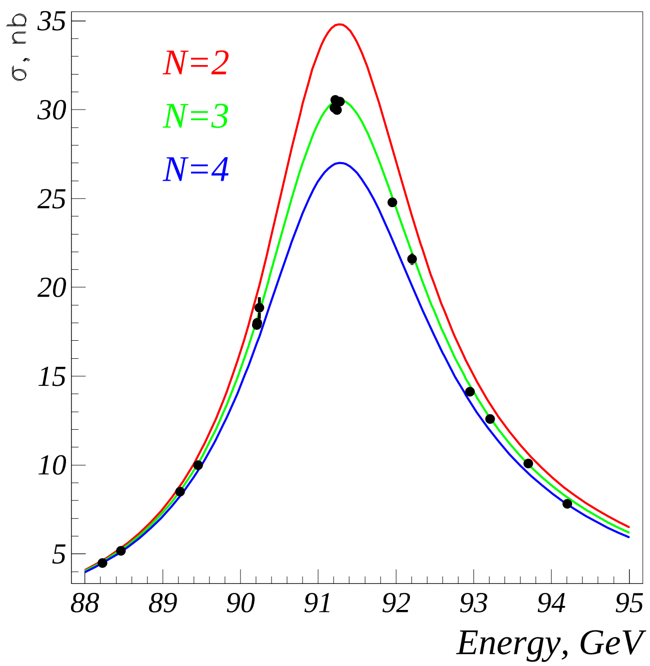


Figure 3.1: The LEP Z line shape measurements compared to the predictions for 2, 3 and 4 light neutrinos.

Electroweak physics was the main aim of LEP-I. Before the start up of LEP in 1989 the Z mass was known from UA2 and CDF with a precision of 350 MeV and its width with an error of 1.5 GeV. By measuring the line shape, *i.e.*, the cross section as a function of the centre-of-mass energy the Z mass and width and the number of light (w.r.t. the Z mass) neutrino species could be measured. The final Z line shape is shown in Figure 3.1. In March 1990 the combined LEP results gave a precision of 34 MeV on the Z mass and 38 MeV on its width. More importantly the number of light neutrino families was 3.04 $\pm$0.14. This was the first solid evidence for the existence of only three generations.

The LEP machine worked remarkably well and in the years up to 1995 large data sets around the Z pole were taken corresponding to typically 4 million hadronic Z decays per experiment. This allowed precision measurements to be performed. With the purpose of combining the LEP results, LEP working groups were formed.

One example of the improvement is the measurement of the Z mass. Its error decreased from the 34 MeV quoted above to 2.1 MeV as shown in Figure 3.2. This was only possible because of the improved understanding of the calibration of the LEP energy. To understand fluctuations in the measurements it was found that the tidal influence of the moon affected the energy of the LEP accelerator. Also the water level in Lake Geneva and TGV trains running on the route near CERN affected the measurement. After understanding these effects a precision of 23 ppm could be reached. This makes the Z mass one of the most accurately known fundamental constants.

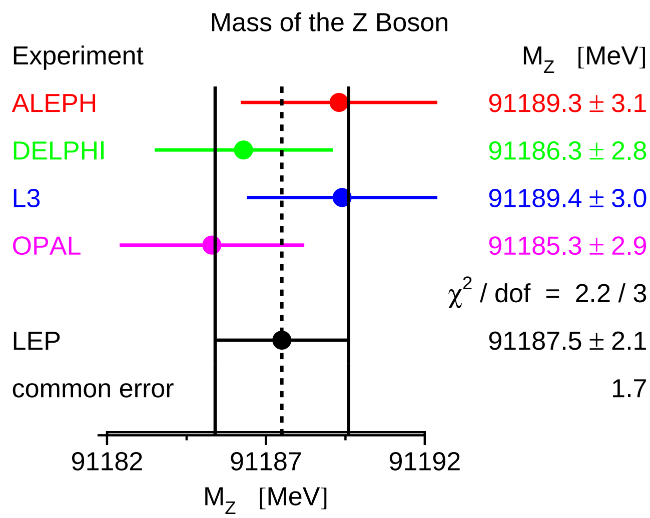


Figure 3.2: The mass of the Z boson for the different LEP experiments.

The number of light neutrino species is determined from the LEP line shape data to be 2.9841 ± 0.0083. This is in good agreement with there being three families. This result is also important because it can be used to exclude other new light (w.r.t. the Z) invisible particle(s) that couple to the Z.

The LEP experiments measured to high accuracy the basic couplings of the Z boson to leptons (electrons, muons, taus) and quarks (up-type and down-type). In the Standard Model the vector and axial-vector couplings are the same for all leptons, the same for all up-type quarks and for all down-type quarks. Their values can be expressed as a function of the quantum number I_3, the electric charge Q and the effective weak mixing angle $\sin\theta_{\text{eff}}$.

The results for the leptons are summarised in Figure 3.3. The two basic couplings g_{A} and g_{V} are derived from two main observables: the measured branching ratio of the Z into leptons and the forward-backward asymmetry. By comparing the results for the different lepton species: electrons, muons and taus, lepton universality is tested at the 3 per mille level.

In the early nineties the top quark had not yet been discovered. In summer 1992 the LEP combined measurement of the $\text{Z} \to \text{b}\bar{\text{b}}$ partial width was 373 ± 9 MeV. This was the strongest evidence that the top quark, the partner of the b-quark, must exist, since this partial width was predicted to be about 370 MeV for $I_3^{\text{b}} = -1/2$ and 24 MeV for $I_3^{\text{b}} = 0$. The precise LEP data were, however, also becoming sensitive to the value of the top mass through electroweak

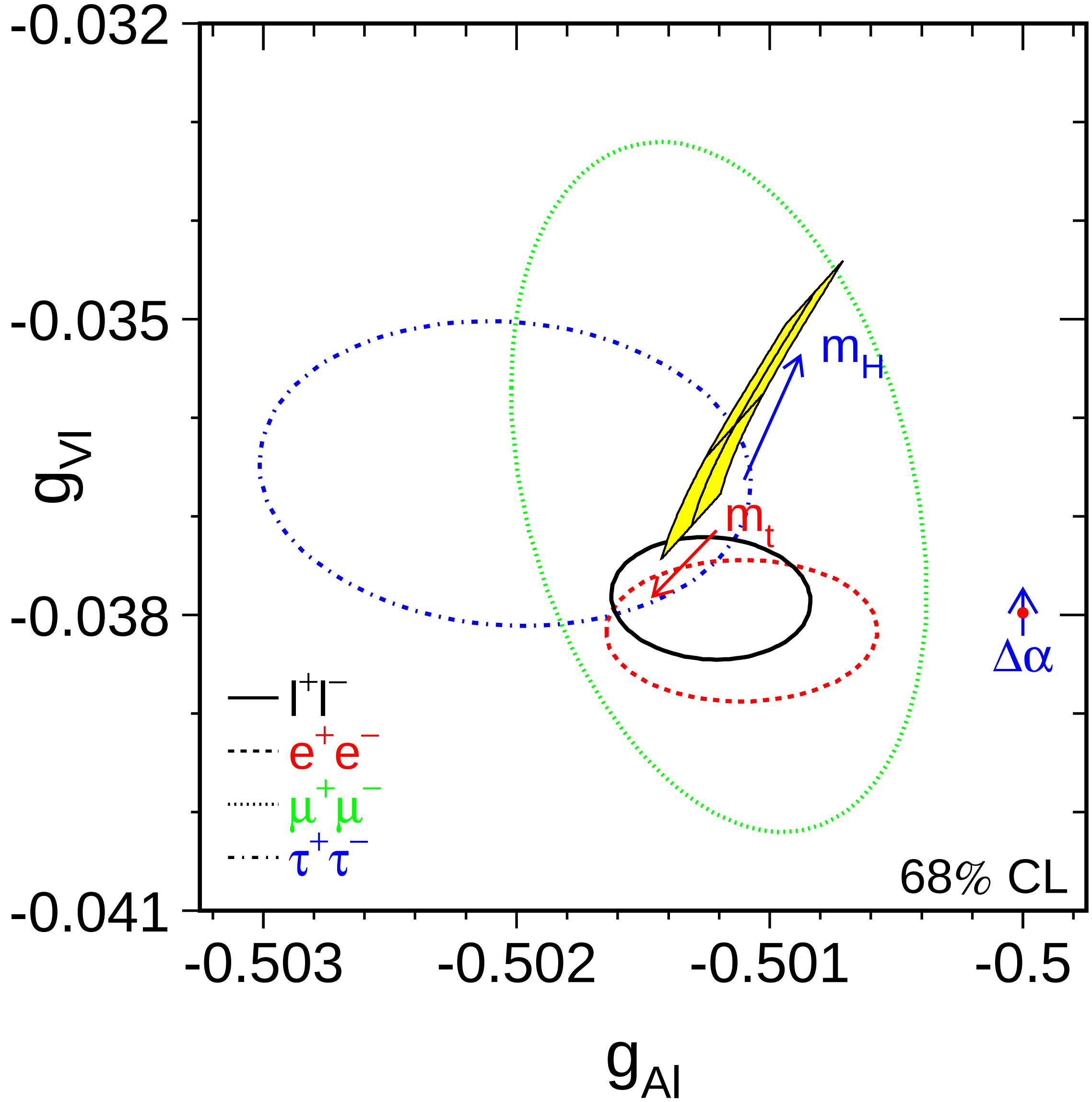


Figure 3.3: The couplings g_{A} and g_{V} for leptons (electrons, muons, taus) and the predictions.

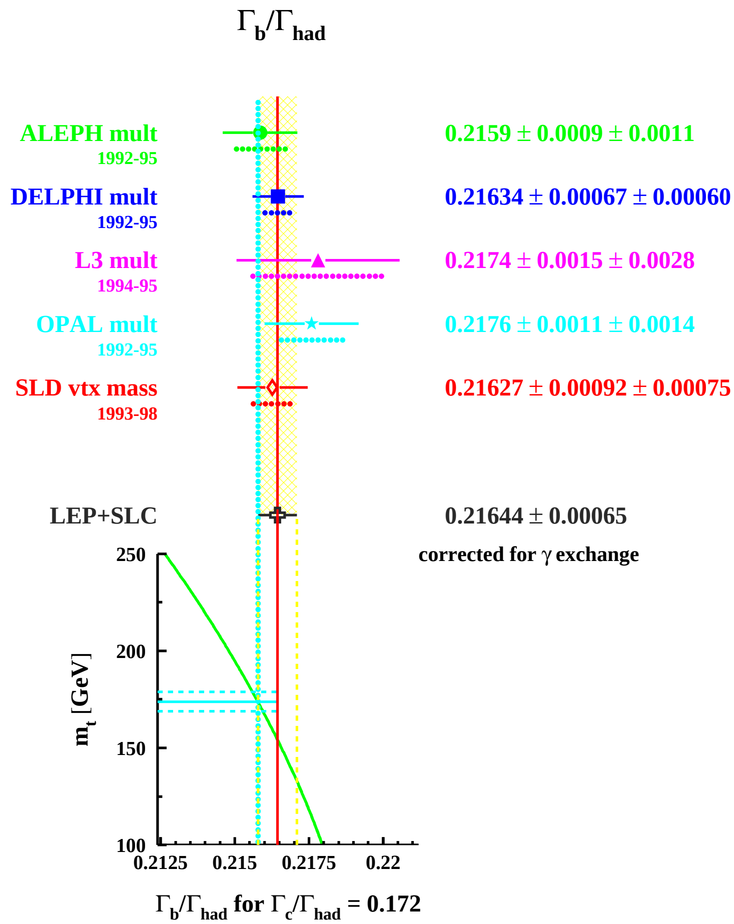


Figure 3.4: The ratio $\Gamma_{\mathrm{b\bar{b}}}/\Gamma_{\mathrm{h}}$ for the LEP experiments.

loop corrections. In summer 1994 the prediction for the top quark mass was $m_{\mathrm{t}} = 173^{+12+18}_{-13-21}$ GeV, while CDF reported 174^{+10+18}_{-10-23} *"if the excess is due to top."* A year later both CDF and D0 reported *"observation"* of the top quark. The correct prediction of the top mass was a major triumph of LEP and the Standard Model.

The introduction of silicon microvertex detectors made it possible to reconstruct events with a b ($\bar{\mathrm{b}}$) quark with high efficiency and purity. The typical decay distance of a b quark is about 4 mm. Using the precise track reconstruction, the B decay vertex can be reconstructed and B events can be tagged. By using singly and doubly tagged events, the fraction of $\mathrm{b\bar{b}}$ quark events could be determined with a precision of 3 per mille, as shown in Figure 3.4. The same technique enabled the measurement of the forward-backward asymmetry and the determination of the effective weak mixing angle. The result, shown in Figure 3.5, is one of the most precise electroweak measurements. The asymmetry differs by slightly more than two standard deviations from the Standard Model. This is further discussed in the Conclusions.

Many other electroweak measurements were performed at LEP-I and a summary of these results is shown in Figure 3.5. The Fermi decay constant G_{F}, and the electromagnetic and strong coupling constants ($\alpha_{\mathrm{em}}(m_{\mathrm{Z}})$, $\alpha_{\mathrm{s}}(m_{\mathrm{Z}})$) are an input to the electroweak Standard Model fit. The Higgs mass is the only free parameter. This topic will be discussed later in Section 4.2.

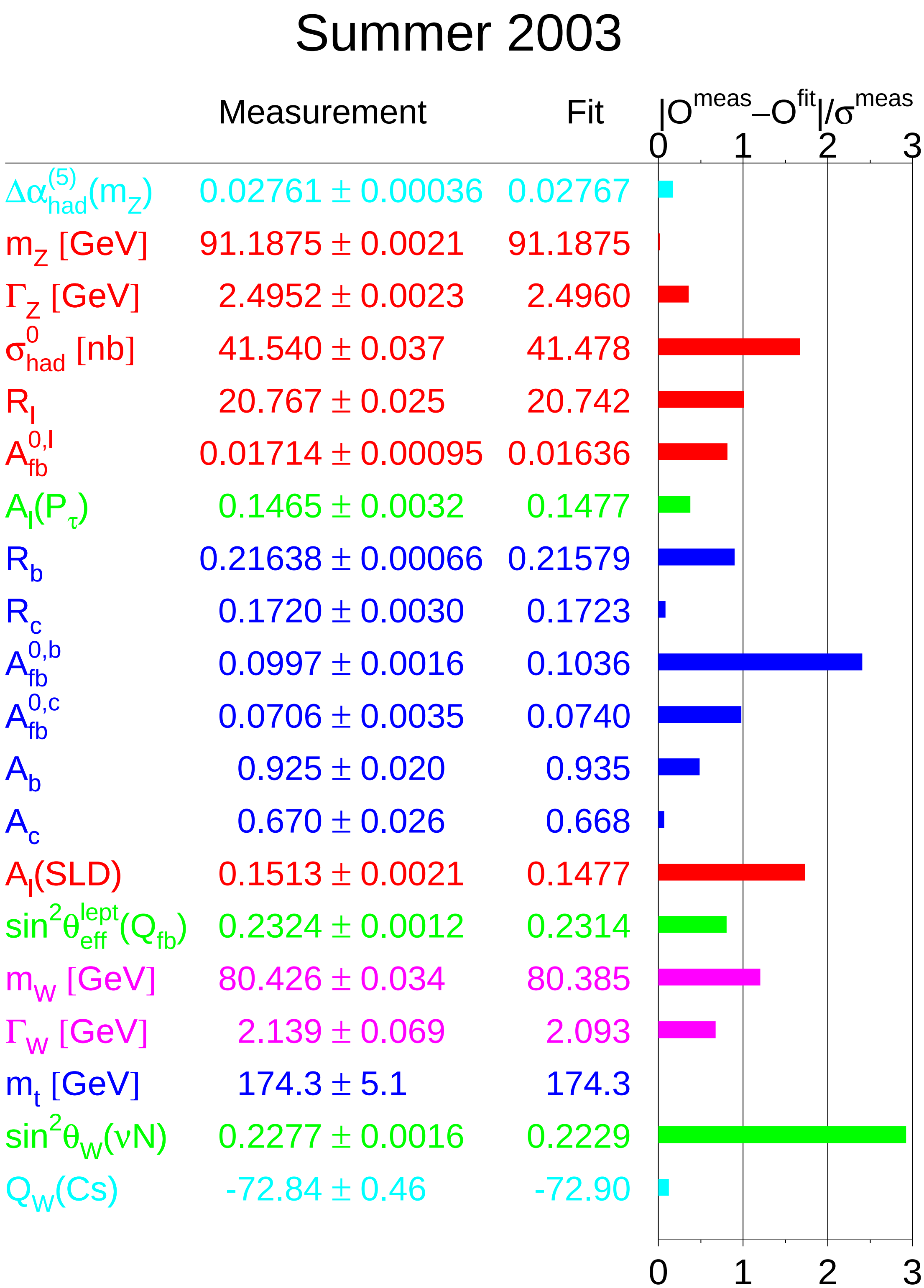


Figure 3.5: The LEP results compared to the electroweak Standard Model fit, including results from LEP-II and other experiments.

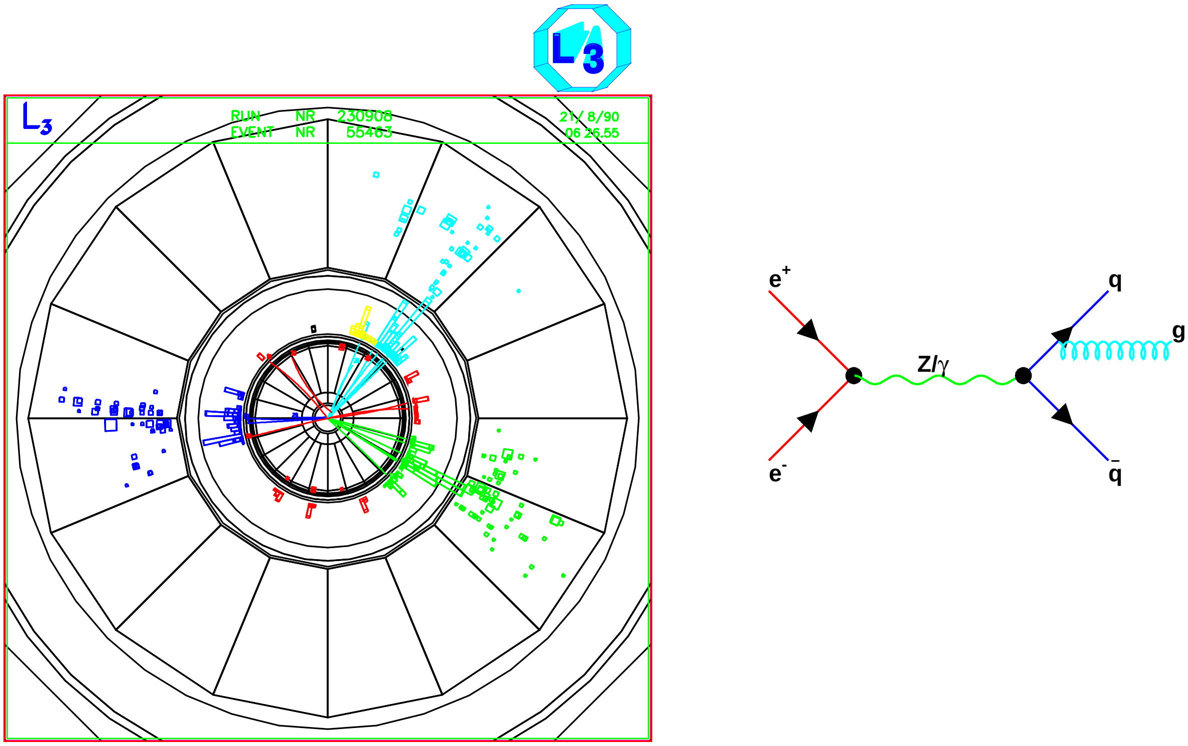


Figure 3.6: Event display of a 3-jet event and the Feynman diagram of the 3-jet process.

3.2 QCD

Although Quantum Chromo-Dynamics (QCD) was, at the start of LEP the best candidate for the theory of the strong interactions, many of its features had not yet been rigorously tested. Hadronic events produced in e^+e^- annihilation provide an exceptionally clean environment to test the predictions of QCD, since QCD only affects the final state. The observed hadronic event structure is directly related to the gluon radiation pattern produced in the QCD processes. At the high energy of LEP, the produced partons fragment into easily recognisable jets of hadrons, as illustrated for a 3-jet event in Figure 3.6.

Since QCD is a non-Abelian gauge theory, its gauge bosons, called gluons, have a self-interaction. The number of gluons as well as the relative strength of the qqg, ggg, $\mathrm{gq\overline{q}}$ couplings depend on the gauge group, as shown in Figure 3.7 through the Casimir factors of the group, C_F, C_A, T_F. These couplings are directly studied in 4-jet events, which are produced via the diagrams shown in Figure 3.7, each quark or gluon being detectable as a jet. The relative contributions of these processes are measured by fitting angular distributions of the jets. The results, shown in Figure 3.8, are consistent with SU(3) and establish the existence of the triple-gluon coupling. In the figure comparison is also made to the predictions of other gauge groups. However, all except SO(3) and $\mathrm{U}(1)_3$, an Abelian vector gluon model, had already been ruled out, *e.g.*, by the knowledge from the hadronic cross section in e^+e^- annihilation, that the number of quark colours, N_C, is 3. The results of Figure 3.8 also rule out these two groups.

Apart from the quark masses, QCD contains only one free parameter, the strong coupling constant, α_s. which depends, in a prescribed way on the scale of the interaction, decreasing as the scale increases. This is usually referred to as the "running" of α_s. By convention, α_s measurements are usually reported at the scale of the Z mass, since measurements at LEP-I

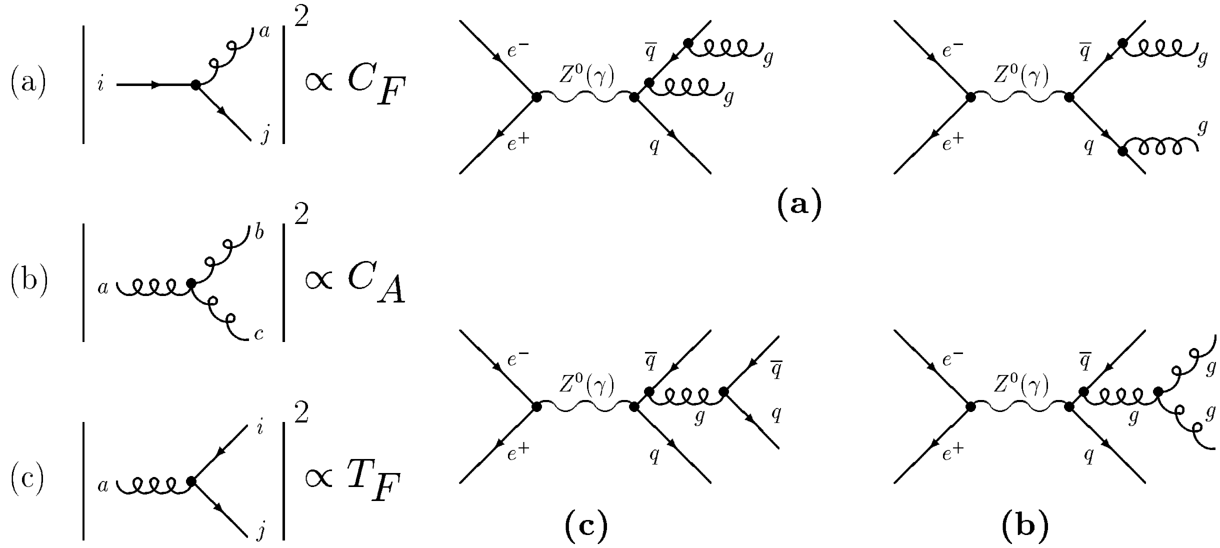


Figure 3.7: The triple parton couplings and their dependence on the Casimir factors (left) and the 4-jet processes in which these couplings occur (right).

have provided some of its most accurate measurements. Since the couplings of quarks and gluons (Figure 3.7a–c) depend directly on α_s, its value can, in principle, be determined from the characteristics of any process involving a gluon. At LEP, α_s has been measured in a variety of ways. The most direct is the measurement of the 3-jet rate, the fraction of 3-jet events, which are produced according to the Feynman diagram shown in Figure 3.6. The distributions of so-called event-shape variables, which depend on the number and distribution of radiated gluons, can also be used to determine α_s. The values of α_s obtained by the various methods are compatible.

The predictions of QCD do not depend on the flavour of the quarks involved in the process. This is indeed found to be the case by measuring α_s for events of different flavours.

As a consequence of the running of α_s, perturbative calculations can only be performed at large energy scales, where α_s is sufficiently small. For the non-perturbative part, the hadronisation phase, models have to be used. Monte Carlo programs JETSET, HERWIG, and ARIADNE start off with the results from the perturbative calculations and then use a model to hadronize and decay the particles. These models were carefully tuned to the LEP-I data.

It is difficult to overemphasise the importance of these Monte Carlo programs. Firstly, their ability to describe well distributions for the process $e^+e^- \to q\overline{q} \to$ hadrons is in itself a test of QCD. An example is the effect of interference which is absent at the lowest order of perturbation theory. Certain correlations are described well only when these effects are included in the Monte Carlo programs.

The success of these programs in describing the data enables their use to correct the analytic calculations at the parton level for the effects of the hadronisation of the partons. This is of importance, *e.g.*, in the measurement of α_s, where the parton-level calculations must be compared to hadronic distributions. Furthermore, these programs provide the background calculations for the study of other processes, *e.g.*, the search for the Higgs boson, *cf.* Section 4.2, or for other new particles.

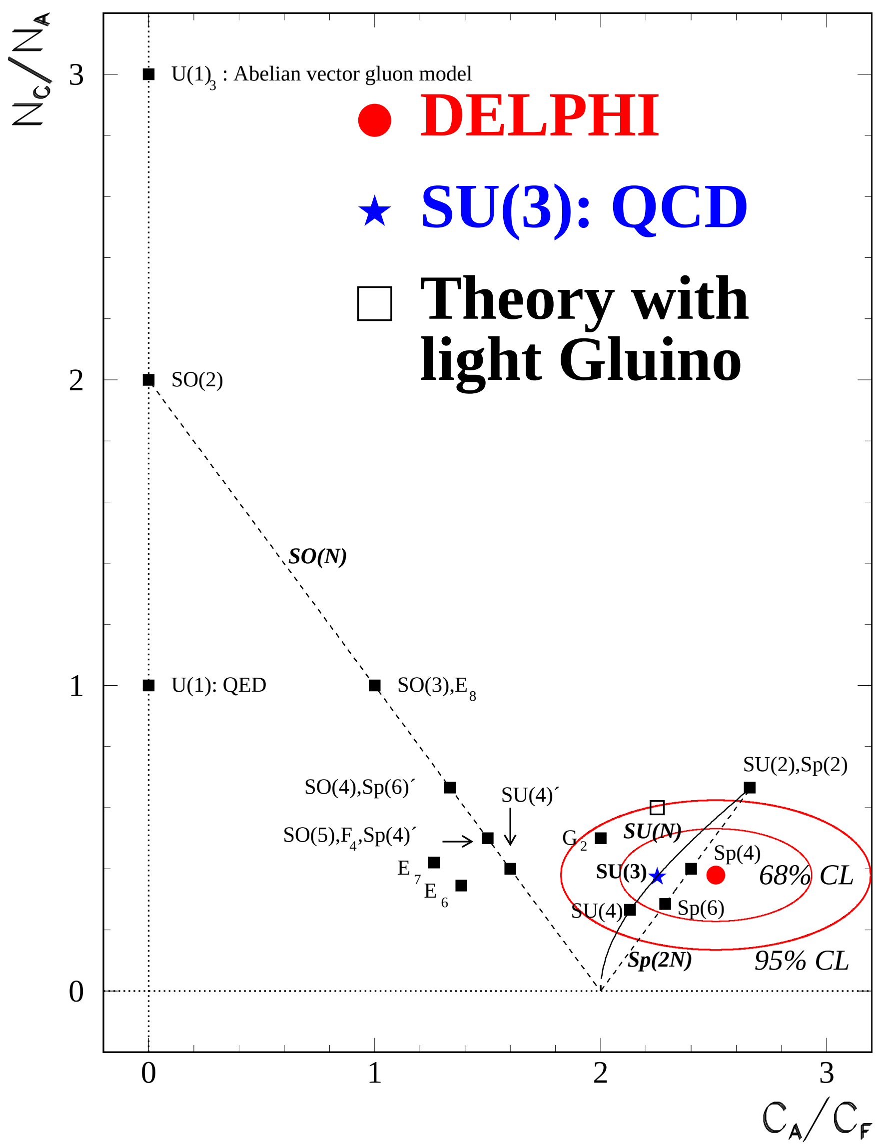


Figure 3.8: 68% and 95% CL contour plots for the measured variables C_A/C_F and $T_F/C_F = N_C/N_A$ compared to the expectations of various gauge groups as well as a theory with a light gluino.

3.3 Heavy Flavour physics

Heavy flavour physics was not part of the original LEP programme in the seventies, because the bottom quark and the τ lepton had not yet been discovered. In the studies performed in 1978, τ, bottom and top physics were added. In general, much more (and with much higher precision) was achieved than was originally anticipated.

The LEP machine was an ideal environment to study the production and decay properties of the τ lepton. At the Z pole the τ lepton is produced polarised, and its polarisation can be analysed in its leptonic and hadronic decays. The combined LEP result for the τ polarisation P_τ is shown in Figure 3.5. The result is very sensitive to the effective weak mixing angle.

The introduction of silicon microvertex detectors enabled precise measurements of the τ lifetime using one- and three-prong decays. In the Standard Model the τ lifetime can be related to the μ lifetime, the μ mass, the τ mass and the leptonic τ branching ratio. In Figure 3.9 the results for 1990 and the LEP situation in 2000 are shown. The year 2000 prediction (green band) includes the improved measurement of the τ mass by BES. This means that (e-)μ-τ universality is tested at the few per mille level.

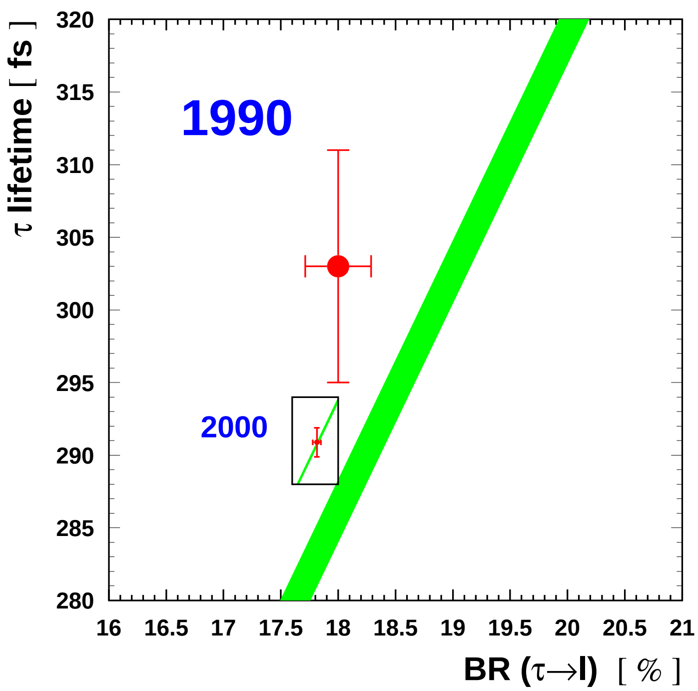


Figure 3.9: The measured τ lifetime *vs.* the τ leptonic branching ratio. The situation is shown before (1990) and after (2000) the improved τ lifetime and τ mass measurements. The bands represent the predictions in the two years.

The vertex detectors also boosted the field of B physics. New particles were discovered: the B_s^0 meson, the Λ_b and Ξ_b baryons and the orbitally excited B^{**} mesons. Precision measurements were performed of the lifetimes of the different B hadron species. Predictions of heavy quark effective theory (HQET) for lifetime ratios were tested at the few percent level, as shown in Figure 3.10. There might still be a problem with the B baryon lifetime.

The LEP experiments worked hard to compete with the CLEO experiment to contribute to the knowledge of the CKM matrix and the role of CP violation. The 3×3 complex unitary

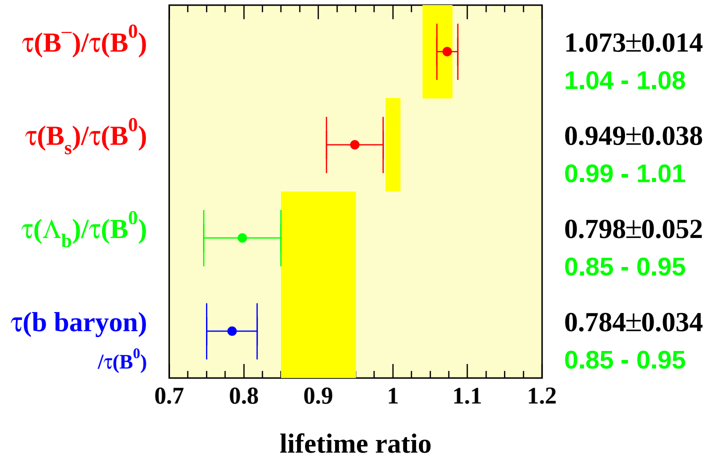


Figure 3.10: The measured and predicted lifetime ratios for the different B hadrons.

CKM matrix describes the coupling of the charged W boson to the different quarks. B physics at LEP gives access to the following elements:

- $|V_{\rm td}|$ from $\rm B^0_d - \overline{B^0_d}$ oscillations;
- $|V_{\rm ts}|$ from $\rm B^0_s - \overline{B^0_s}$ oscillations;
- $|V_{\rm cb}|$ in semileptonic $\rm b \to c\ell\nu$ transitions; and
- $|V_{\rm ub}|$ in semileptonic $\rm b \to u\ell\nu$ transitions.

At LEP $\rm B^0_d - \overline{B^0_d}$ oscillations were discovered and the oscillation frequency $\Delta m_{\rm d}$ measured with a total precision of 2.5%.

Searches for $\rm B^0_s - \overline{B^0_s}$ oscillations, which are expected to be about 20 times faster than $\rm B^0_d - \overline{B^0_d}$ oscillations, were performed. $\rm B^0_s$ mixing is established, but no compelling evidence for oscillations could be claimed, and a limit on the oscillation frequency was put at $\Delta m_{\rm s} >$ 14.9 $\rm ps^{-1}$.

Detailed analysis of semileptonic B decays allowed values of $|V_{\rm cb}|$ and $|V_{\rm ub}|$ to be extracted from measurements of the branching ratio and the b lifetime .

For the CKM matrix, the Wolfenstein parametrisation is used. It has three real parameters, λ, A and ρ, and one complex parameter, η. If η is non-zero, CP violation is present. The different LEP measurements can be projected onto the ρ-η plane, as shown in Figure 3.11, where:

- LEP results for $|V_{\rm ub}|/|V_{\rm cb}|$ correspond to the green shaded circle at (0,0);
- the $\rm B^0_d - \overline{B^0_d}$ oscillation results correspond to the red shaded circle at (1,0);
- the limit on $\Delta m_{\rm s}/\Delta m_{\rm d}$ corresponds to the black circle at (1,0) and excludes the outer part of the red circle; and,
- the results for CP violation in the kaon system $\epsilon_{\rm K}$ correspond to the blue hyperbola.

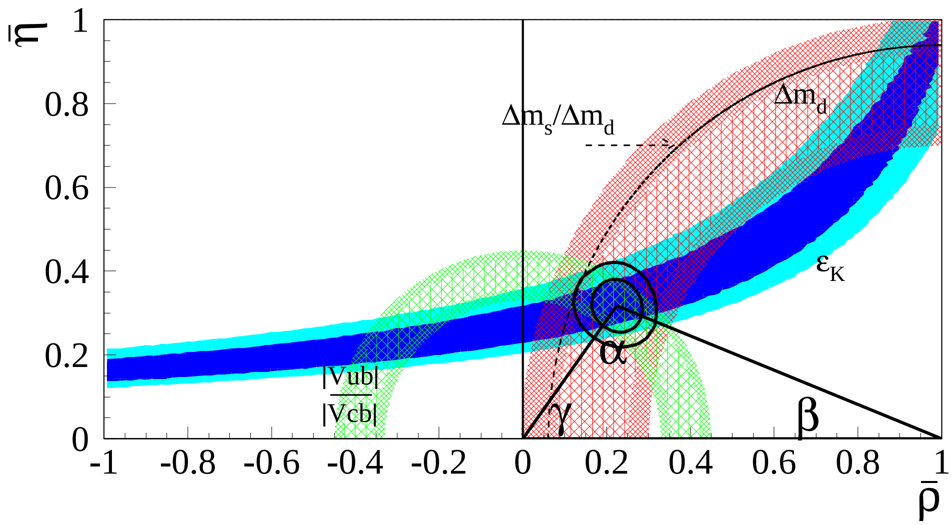


Figure 3.11: The different LEP B physics measurements and ϵ_K projected onto the $\rho - \eta$ plane in March 2000.

The different results are compatible with a single point in the $\rho - \eta$ plane. Using just the LEP measurements it can be concluded that η is non-zero and CP is violated in the B system. The predictions for ρ and η are in perfect agreement with the direct observation of CP violation in the B system by the B factory experiments in 2001.

The contribution of LEP-I to the understanding of the CKM matrix are summarised in Figure 3.12. The achieved precision is far beyond what was anticipated in studies performed in 1978.

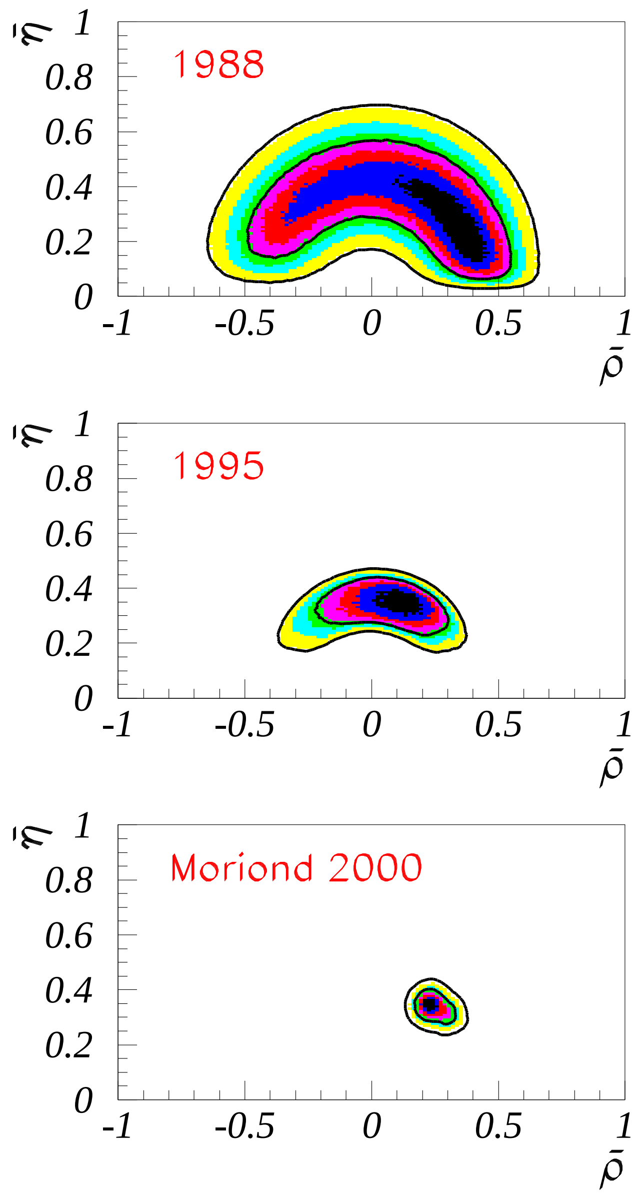


Figure 3.12: The evolution during the years 1988 to March 2000 for the allowed region in the ρ-η plane (contours at 68% and 95%).

Chapter 4

The LEP-II physics programme

The main topics of interest at LEP-II were the properties of the W boson, the search for the Higgs boson, and the "running" of the strong coupling constant. The cross sections for the relevant channels are shown in Figure 4.1. Searches for new particles, not included in the Standard Model, also occupied an important part of the LEP-II programme.

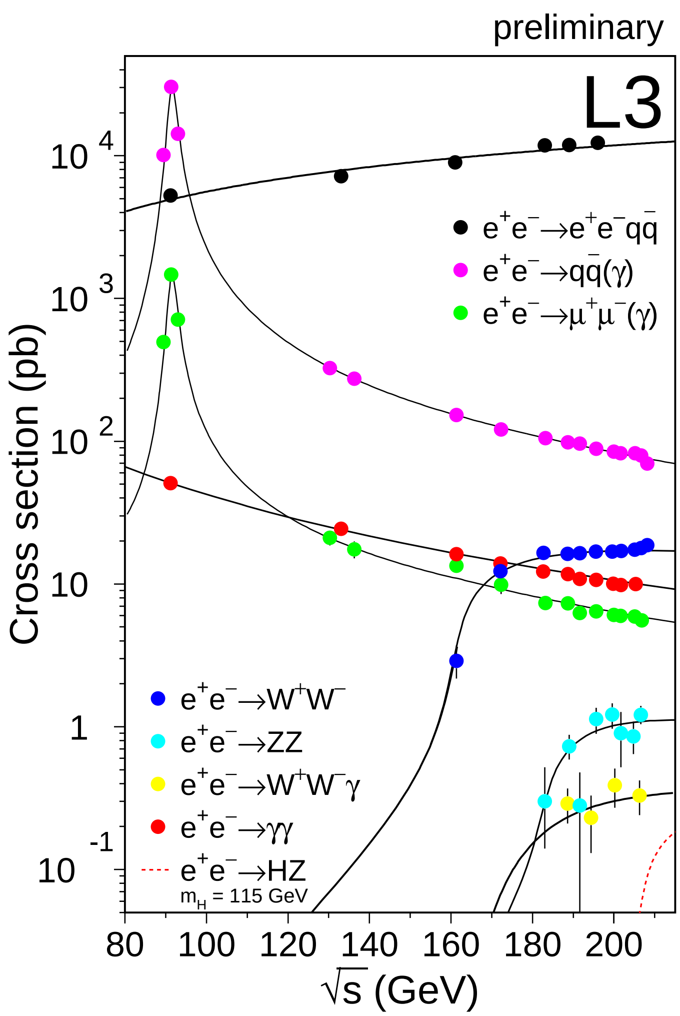


Figure 4.1: Standard Model cross sections in the energy range of LEP with preliminary L3 measurements.

4.1 W physics

Following the precise measurements of LEP-I, the properties of the W-boson could be predicted by the Standard Model with good precision. The goal at LEP-II was, therefore, to see whether these predictions were valid.

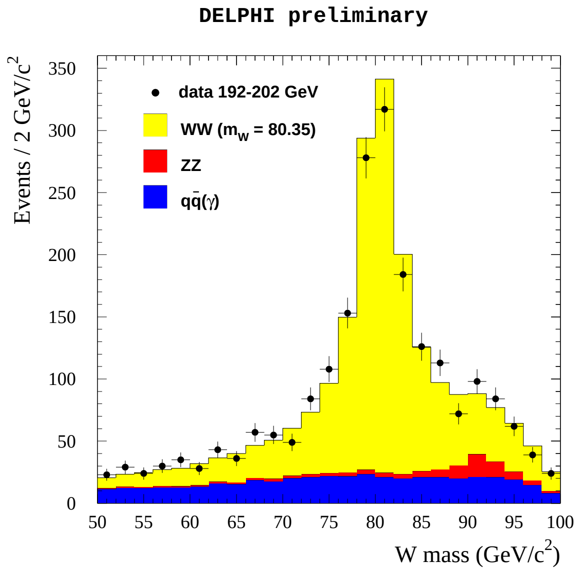


Figure 4.2: The invariant mass distribution for "fully-hadronic" W pair events.

Before 1996, measurements of W properties came exclusively from the $p\bar{p}$ colliders. At that time the LEP centre-of-mass energy was increased to 161 GeV, just above the W-pair threshold. There the cross section is small, but strongly dependent on the precise value of the W mass. Comparison of the measured cross section to that calculated in the Standard Model as a function of the W mass enabled its first LEP measurement. Later the centre-of-mass energy was increased further, resulting in a much higher W-pair cross section. The mass and width of the W could then be measured directly by reconstructing the W's, both in the "semi-hadronic" channel, where one W decays hadronically and the other leptonically, and the "fully-hadronic" channel, where both decay hadronically. In Figure 4.2 the invariant mass distribution for the "fully-hadronic" channel is shown.

The preliminary measurements of the W mass and width are in agreement with the expectations of the Standard Model, as are the branching ratios of the W. The present value of the mass obtained by averaging the preliminary values from the four LEP experiments is 80.412 ± 0.042 GeV. For comparison, the average from $p\bar{p}$ colliders is 80.454 ± 0.059 GeV. These values agree well with those predicted in the Standard Model on the basis of measurements of Z properties at LEP-I and SLD and the mass of the top quark measured at the TeVatron: 80.378 ± 0.023 GeV.

The existence of triple-gauge-boson vertices is a consequence of the non-Abelian gauge structure of the electroweak theory. To lowest order, three Feynman diagrams contribute to W-pair production, as shown in Figure 4.3. The two s-channel graphs involve such vertices, namely γWW and ZWW. The necessity of more than just the t-channel ν-exchange diagram can be seen from the WW cross section shown in Figure 4.3. In general each is parametrised in terms of seven triple-gauge-boson couplings (TGCs). Retaining only CP-conserving couplings and assuming electromagnetic gauge invariance, gives six couplings. At tree level in the

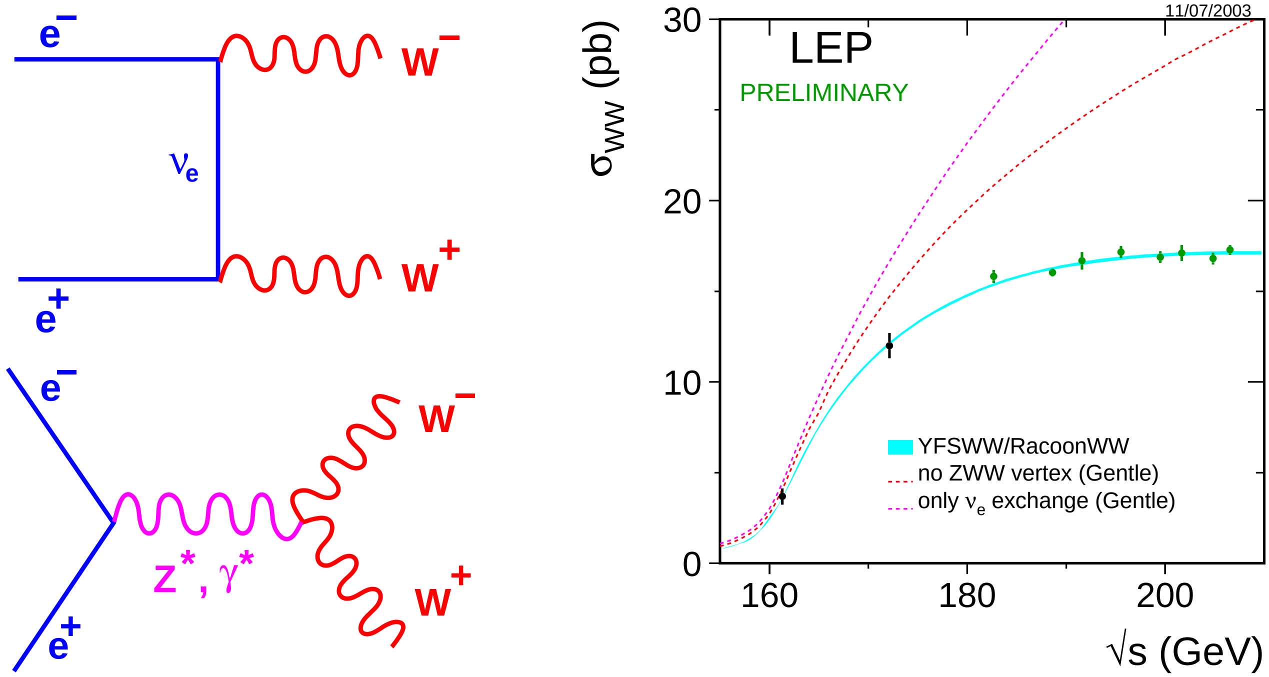


Figure 4.3: Tree-level Feynman diagrams for the reaction $e^+e^-\to W^+W^-$ and its cross section as function of centre-of-mass energy compared to predictions.

Standard Model they have the values $\kappa_\gamma = \kappa_Z = g_1^Z = 1$ and $\lambda_\gamma = \lambda_Z = g_5^Z = 0$. The distribution of the W production angle and the polar and azimuthal decay angles of the W^+ and W^- in their rest frames, as well as the W^+W^- production cross section depend on the values of these TGCs. From an analysis of these distributions the values of the TGCs are extracted. The cross section for $e^+e^-\to e\nu W$ depends on κ_γ and λ_γ. These TGCs are also measured in this channel and can be combined with the results of the W^+W^- analysis. An example of these results is shown in Figure 4.4. The TGCs are found to be consistent with the Standard Model expectations.

As for W^+W^-, the final state ZZ provides access to the ZZZ and γZZ TGCs, while the final state γZ provides access to the $\gamma\gamma$Z and ZγZ TGCs. These couplings are all zero at tree level. Statistics are too small to analyse angular distributions. However, the cross sections are found to be in agreement with Standard Model predictions.

Quartic couplings are also investigated. The cross section of $e^+e^-\to W^+W^-\gamma$ is affected by $\gamma\gamma$WW and ZγWW quartic couplings. At LEP centre-of-mass energies these contributions are, according to the Standard Model, negligible, and this is found to be in agreement with the data.

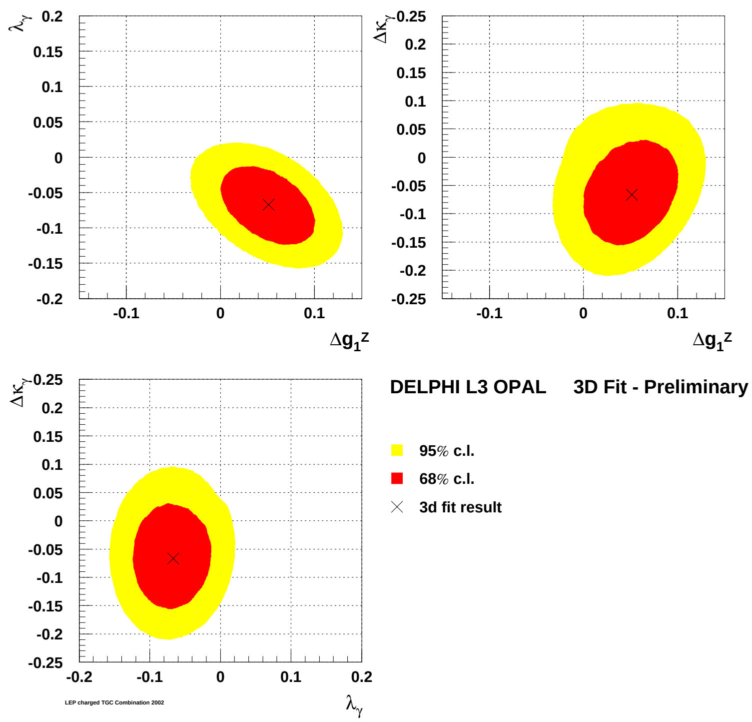


Figure 4.4: Confidence limits on the ZWW and γWW TGCs λ_γ, $\Delta\kappa_\gamma$ and Δg_1^Z, where Δ indicates difference from the Standard Model value.

4.2 Higgs and new particle searches

Searching for the Higgs boson and other new particles was one of the main aims of LEP-I and LEP-II. LEP is a perfect environment to perform these studies, because of the theoretically well-understood initial (and final) state, and well-understood high-performance hermetic detectors.

Before the start-up of LEP no exclusion for a Higgs mass around zero or above 3.6 GeV existed, and in the mass region in between only small bands were excluded. By March 1990 the Higgs was already excluded in the mass range of 0–25 GeV and in the summer of the same year the mass limit went up to 44 GeV. The full LEP-I data set excludes the region up to a Higgs mass of 66 GeV.

A large effort went into the search for other new particles: heavy stable particles, charginos, neutralinos, sleptons, squarks, charged Higgses, excited leptons, fourth family quarks and leptons and the top quark. None of these particles was found, and for most cases the mass limit reached the kinematic limit of $\sim m_{\mathrm{Z}}/2$.

With the increased energy of LEP-II, the Higgs search entered a new phase. At the Aachen workshop in 1986 it was considered experimentally difficult to explore the region $m_{\mathrm{H}} \approx m_{\mathrm{W}}$ and impossible to reach $m_{\mathrm{H}} \geq m_{\mathrm{Z}}$. Using procedures based on the silicon microvertex detector to tag b quarks, together with sophisticated analysis techniques it was possible to go beyond m_{W} and m_{Z} to reach a final limit of $m_{\mathrm{H}} \approx \sqrt{s} - m_{\mathrm{Z}}$. In the last year of LEP running the energy was increased to about 208 GeV and a hint of a Higgs signal at a mass of about 115 GeV was presented in November 2000 with a combined significance of 2.9 standard deviations. The data have been further analysed and the final significance of the signal is less, about 1.7 standard deviations, as shown in Figure 4.5. The combined LEP result for the Higgs is: $m_{\mathrm{H}} > 114.4$ GeV at 95% CL.

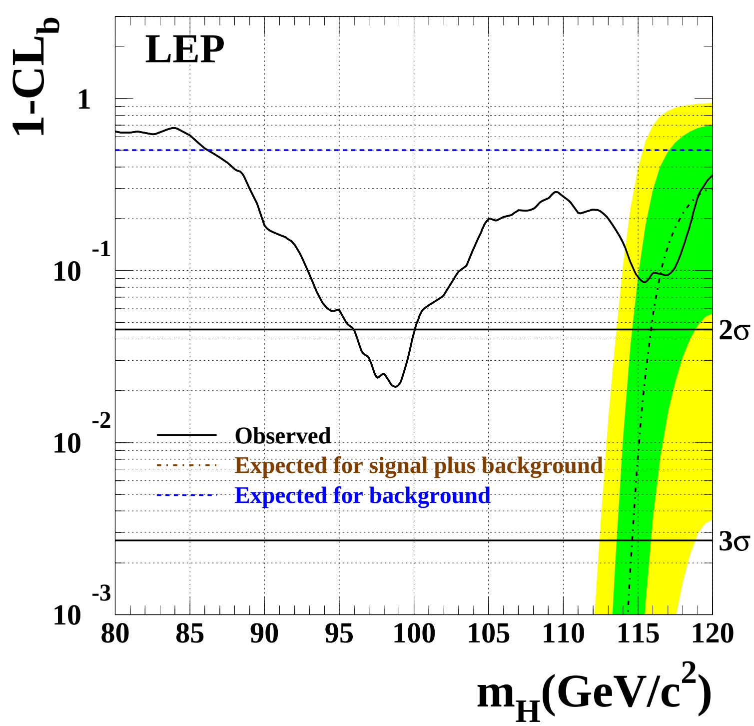


Figure 4.5: The background confidence $1 - \mathrm{CL_b}$ as a function of the Higgs mass.

The search for new exotic physics continued at LEP-II, with particular emphasis on supersymmetry (SUSY). SUSY is strongly advocated by theorists, because it solves a number of problems inherent in the Standard Model. The unification of the coupling constants—electromagnetic, weak and strong—at very high energy and the correct prediction of the effective weak mixing angle make the theory very appealing. Unfortunately, SUSY has about 124 new parameters and one needs a model (*e.g.*, SUGRA, GMSB, AMSB) to reduce the number of parameters. This makes the analyses model dependent. Searches for the lightest supersymmetric particle (*e.g.*, neutralino or gravitino), for (stable) sleptons, squarks and charginos were all unsuccessful. Most of the exotic or SUSY particles are excluded by LEP-I and LEP-II for masses below $\sqrt{s}/2 \approx 100$ GeV. Also one "firm" prediction of SUSY: the existence of a light Higgs boson, h, with a mass below 124 GeV was not confirmed. These results pose a clear naturalness problem for SUSY: almost 99% of the phase space of the SUGRA model is excluded by LEP-I and LEP-II leaving only a narrow escape path.

Let's go back to the Standard Model Higgs. As explained in Section 3.1, one can use the different electroweak measurements to determine the mass of the Higgs. Just as LEP was able to predict, through the effect of electroweak corrections, the mass of the top quark, it is also sensitive to the Higgs mass. The Higgs mass prediction from the electroweak measurements is shown in Figure 4.6. The yellow region corresponds to the part excluded by the direct Higgs search. The curve implies a low-mass Higgs with a mass of less than 219 GeV at 95% CL.

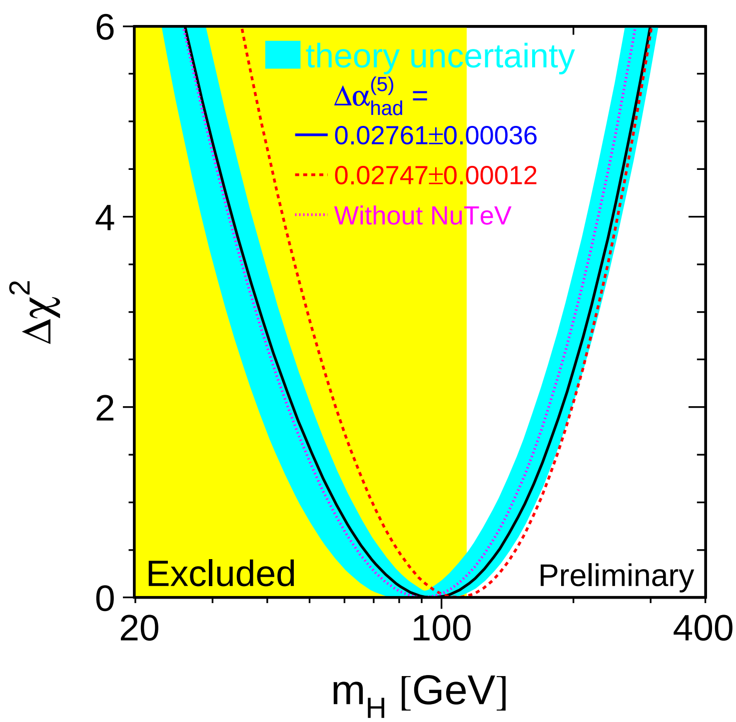


Figure 4.6: The Higgs mass prediction from the electroweak fit.

4.3 QCD

The availability of a large range of centre-of-mass energies enables a number of tests of QCD. Destructive interference between radiated gluons is predicted in calculations which go beyond the leading order of perturbation theory. This results in a smaller increase with energy in the number of particles produced. The data are in agreement with the prediction, as shown in Figure 4.7.

As mentioned in Section 3.2, the strong coupling constant, α_s, is the only free parameter in QCD, apart from the quark masses. The value of α_s depends, in a prescribed way, on the scale of the interaction, decreasing as the scale increases. This is usually referred to as the "running" of α_s.

Event-shape variable distributions have been used to measure α_s not only at LEP-I, but also at LEP-II, and even at effective centre-of-mass energies below the Z-mass. If a LEP-I event has a high energy photon, the energy left for hadronisation is effectively $\sqrt{s'} = \sqrt{s(1 - 2E_\gamma/\sqrt{s})}$. Such events are used to measure α_s at the scale $\sqrt{s'}$. There are thus available within a single experiment a wide range of centre-of-mass energies: 20–206 GeV. When measuring α_s at each energy using the same experimental technique as well as the same theoretical calculation, many of the systematic uncertainties are highly correlated between energies, enabling a more precise determination of the energy dependence of α_s.

To determine the value of α_s using shape variable distributions, the distributions of the shape variables are calculated in QCD, corrected for the effects of hadronization, and fit to the data to obtain the value of α_s.

The results of the four LEP experiments using this technique are being combined by the LEP QCD working group. The measurements of α_s using several shape variables at each of the LEP energies have been combined at each energy, for each shape variable separately, and for all energies and all variables. Preliminary results are shown in Figure 4.7 for each variable. They are consistent.

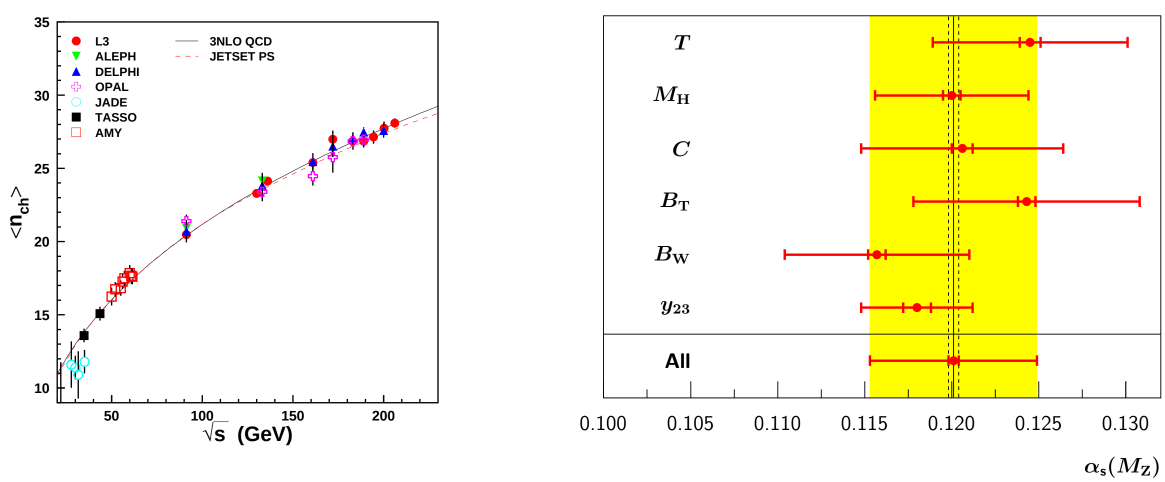


Figure 4.7: The mean charged multiplicity *vs.* the centre-of-mass energy compared to the QCD prediction at next-to-next-to-next-to leading order; and values of $\alpha_s(M_Z)$ from fits to shape-variable distributions by the four LEP experiments. The inner error bars and the dashed lines indicate the statistical uncertainties, while the outer error bars and the band indicate the total uncertainties.

The preliminary combined value of α_s is $\alpha_s(M_Z) = 0.1201 \pm 0.0003 \pm 0.0009 \pm 0.0009 \pm 0.0047$, where the first uncertainty is statistical and the second the experimental systematic uncertainty. The third is the theoretical uncertainty on the effect of hadronization , and the fourth the theoretical uncertainty on the theoretical calculation of the event shape distributions. The experimental measurement is significantly more precise than the theoretical calculation.

In Figure 4.8 the values for each energy are shown and compared to the overall fit result which assumed the QCD prescription of variation with energy. The dominant uncertainty in these results is the uncertainty on the precision of the theoretical calculations owing to the neglect of higher-order terms. Since the systematic uncertainties are highly correlated, they should be largely ignored in comparing the running of α_s with its QCD prediction. It is seen that the data are in agreement with the variation prescribed by QCD.

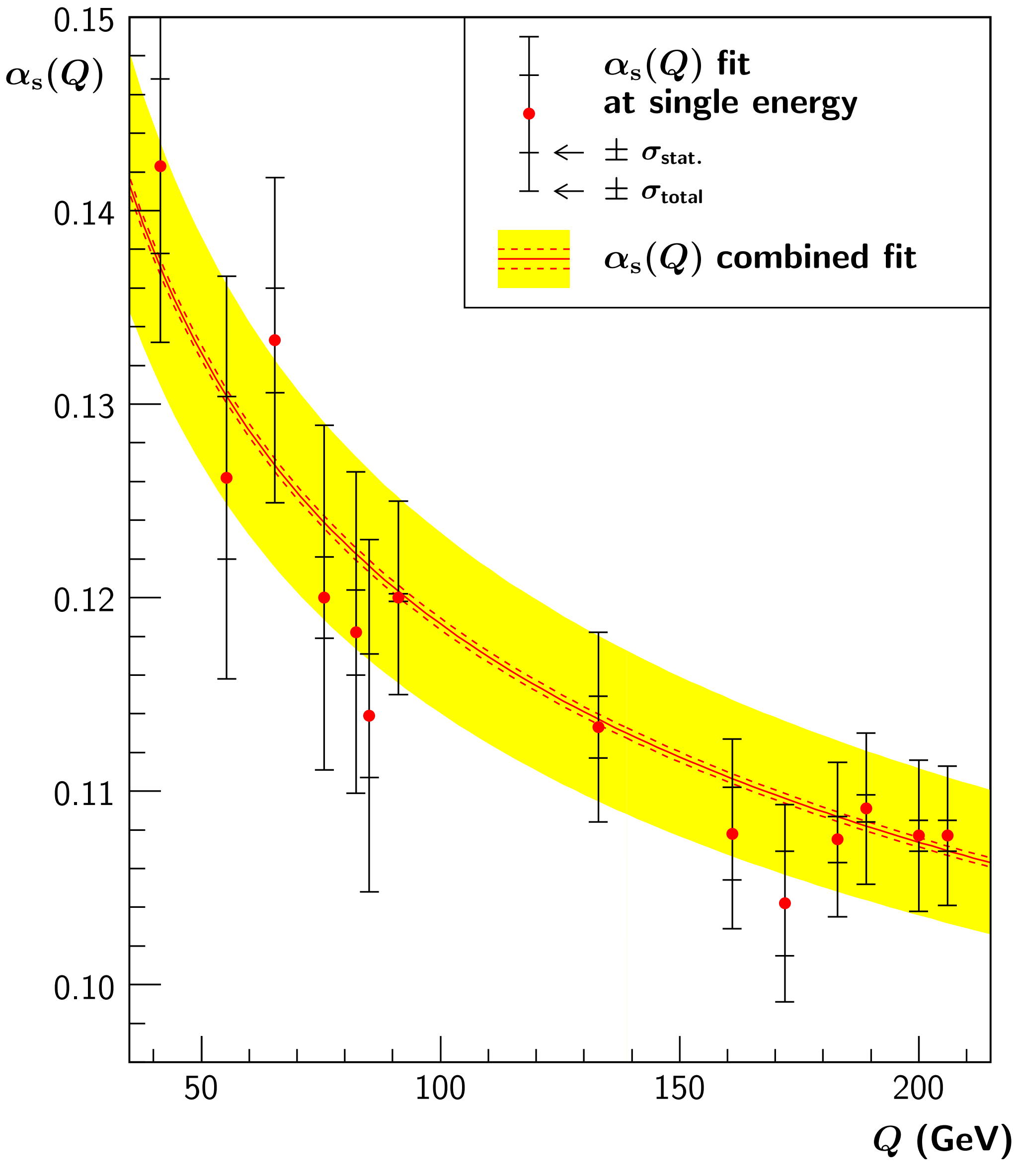


Figure 4.8: Values of α_s from fits to shape-variable distributions by the four LEP experiments for each energy compared to the fit to all energies assuming the QCD dependence on energy. The inner error bars and the dashed lines indicate the statistical uncertainties, while the outer error bars and the band indicate the total uncertainties.

Chapter 5

Cosmic ray muons

Although not originally part of the LEP programme, it was realised that the LEP detectors could also function as detectors of muons produced in atmospheric cosmic ray showers. As mentioned in Chapter 2, the L3 detector was modified to allow collection of cosmic muon data during the time between beam crossings, thus allowing concurrent running with LEP data taking.

Data were collected in 1999 and 2000. In both years combined a total of 12 milliard triggers were recorded, resulting in about 4 milliard reconstructed events. The main purpose was to measure the vertical muon momentum spectrum over two orders of magnitude with unprecedented precision. At a muon momentum of 100 GeV the total uncertainty is less than 3%. Furthermore, the angular dependence of the spectrum has been evaluated. The main result is shown in Figure 5.1 together with the ratio of positive to negative muons as a function of the muon momentum.

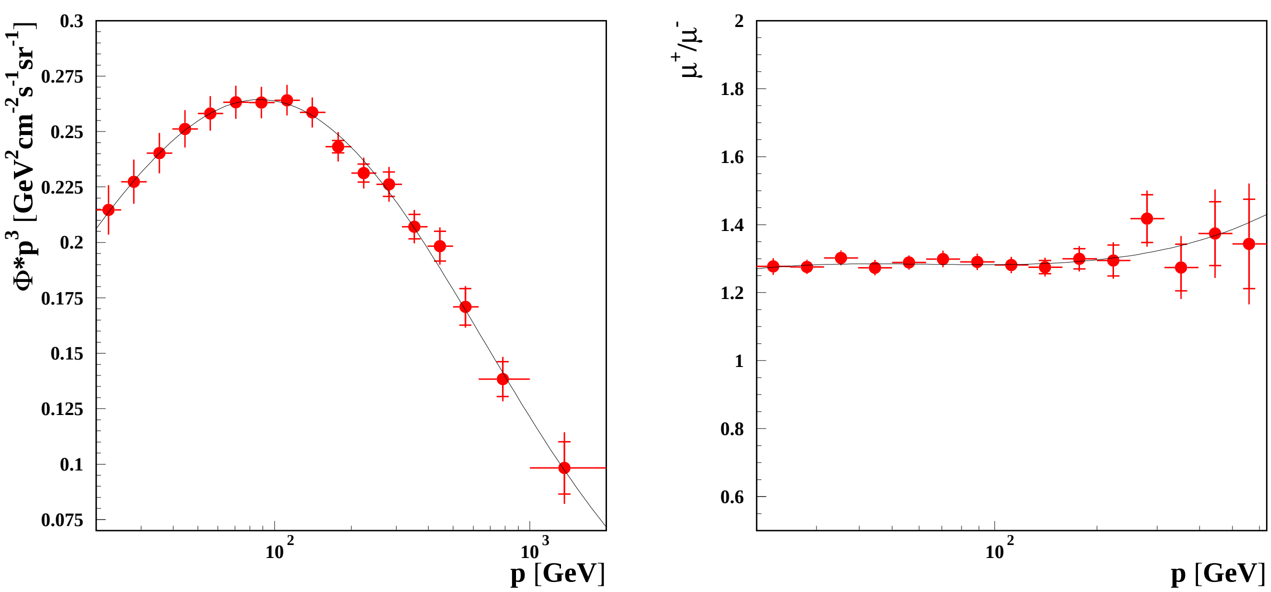


Figure 5.1: The vertical cosmic ray muon spectrum and charge ratio.

Next to the muon spectrum, it was realised that other topics could be studied. Using the moon as an absorber for primary cosmic radiation, and bending of charged particles in the earth magnetic field a measurement can be made for the anti-proton over matter ratio at

cosmic ray energies of about 700 GeV. The resulting upper limit of 0.11 is the only measured limit in this energy region.

The measurement of the moon shadow also allows to precisely know parameters of our detector like the pointing accuracy. This momentum-dependent accuracy of about 0.2 degrees allows for searches of high energetic point sources either stationary, burst-like or pulsars. These searches are still ongoing.

Several other analyses are still ongoing. An example is the correlation of muons observed in the L3 detector with the data recorded in an air-shower array built on the surface above L3. This should yield information about the composition of primary cosmic rays around 10^{15} eV.

Chapter 6

Conclusions: FOM LEP programme

The main LEP results have been summarised in the previous chapters. It is important to discuss the FOM LEP programme and its goals and description (see *Physics at FOM*).

The physics topics mentioned: The measurements of the W boson and its comparison with LEP-I measurements, the test of the existence (and strength) of the coupling of the gauge bosons (TGC) and the Higgs search have been performed. Other topics, like tests of QCD and heavy flavour (B) physics have been completed. For all these topics, more was achieved than was originally planned. The participation in the L3 cosmic programme was also successful.

On all the aforementioned subjects theses have been written (see Appendix A). The staff and Ph.D. students contributed substantially to the final publications on these topics (see Appendix B).

The objectives and main goals of the LEP programme have been achieved due to the excellent performance of the LEP machine, which gave more luminosity and data than anticipated. Due to the combined effort of experimentalists the detectors and underlying physics has improved considerably. On this basis, precision tests of the Standard Model could be performed.

Unfortunately, the Higgs boson was not discovered. And the biggest surprise of all was that there was no surprise: there are no compelling contradictions with the Standard Model—and this is by no means trivial. New experiments will have to uncover the Higgs and the new physics that lies beyond the Standard Model.

Chapter 7

Conclusions: Outlook

The LEP results were summarised by Frank Wilczek in 2000 as: "The historic achievement of LEP has been to establish with an astonishing degree of rigour and beyond all reasonable doubt what will stand for the foreseeable future—perhaps for all time—as the working Theory of Matter ... and to give us some very definite and specific clues for what lies beyond." Despite the large effort of experimentalists and theorists no new physics (*e.g.*, supersymmetry) has been discovered. Looking more closely at the present status of the electroweak fit one can argue that the situation is not that clear anymore. The overall χ^2 of the fit has a probability of only 4.5% and some measurements of the electroweak mixing angle are about 3 standard deviations apart. Whether this is just statistics or a sign of something more complicated in the Higgs sector, is difficult to decide. Future experiments will shed light on this question.

At the Large Hadron Collider at CERN different experiments will take over the torch to answer questions like: What is the origin of mass (Higgs or something else)? Why is there matter and hardly any anti-matter in the universe? The LHCb experiment will probe the latter question by measuring CP violation in finest detail. The ATLAS experiment will perform a crucial test of the Standard Model. It will be able to discover the Higgs particle if it is there. If some other mechanism is responsible for the origin of mass, ATLAS will be able to uncover it. Due to the high energy of the accelerator it will be possible to produce and detect new high mass particles (supersymmetric particles, Higgs bosons, *etc.*). On a longer time scale there exist plans to construct a global Linear e^+e^- Collider that will complement the LHC and take over the LEP legacy.

Appendix A

Ph.D. Theses in The Netherlands

DELPHI

1. H. Jansen, *Photon detection in ring imaging Cherenkov counters*, UL, 6 October 1988.
2. D. Langerveld, *The Technique of Cerenkov ring image detection*, UL, 28 March 1990.
3. A. Rademakers, *The Determination of the Number of Light Neutrino Species*, UvA, 30 January 1991.
4. N. de Groot, *The determination of the branching ratio of the Z^0 boson into heavy quarks using neural networks*, UvA, 9 March 1993.
5. N. Brümmer, *The Lambda baryon as a probe of QCD at LEP*, UL, 3 February 1994.
6. S. Haider, B_s^0 *mixing at the Z^0 resonance determined with the RICH technique*, UL, 8 May 1995.
7. M. Los, *A measurement of the $B^0 - \overline{B^0}$ mixing parameter at LEP using a neural network*, UvA, November 1995.
8. W. Hao, *Study of Charged Kaon Production in Three-Prong Tau Decays*, UL, 1 February 1996.
9. I. Siccama,*Measurement of the* B_s *lifetime*, UvA, 7 October 1996.
10. E. Boudinov, *Measurement of the strange quark forward-backward asymmetry around the Z^0 peak*, UvA, 19 June 2000.
11. M. Mulders, *Direct measurement of the W boson mass in e^+e^- collisions at LEP*, UvA, 5 September 2001.
12. E. Agasi, *Kaon production in τ-decays*, UvA, 18 December 2001.
13. I. van Vulpen, *Measurement of Z boson pair production and a search for the Higgs boson in e^+e^- collisions at LEP*, UvA, 18 April 2002.
14. M. Blom, *Single W measurement at DELPHI*, UvA, 22 April 2003.

There is one additional thesis expected.

L3

1. Y. Peng, *The Muon Spectrometer of the L3 Detector at LEP,* UvA, 1988.
2. J. Onvlee, *The Behaviour of the L3 Muon Chambers in a Magnetic Field,* UvA, 1989.
3. F.M. Smet, *Crystal Growth and Characterization of Bismuth Germinate (BGO),* KUN, 1989.
4. R. Wilhelm, *The L3 Event Visualisation System and its Use in the Z Line Shape Analysis,* UvA, 1992.

5. C.W.J.P. Timmermans, *Measurement of muon pair production around the Z-resonance using the L_3 detector at LEP,* KUN, 1992.
6. M.H.M. Merk, *Study of Bhabha Scattering at the Z^0-Resonance using the L_3 Detector,* KUN, 1992.
7. T. Foreman, *Bottom Quark Production at the Z Resonance,* UvA, 1993.
8. X.J.M. Leijtens, *Production of tau pairs at the Z Resonance,* UvA, 1993.
9. F. Filthaut, *Hadronic Cross Section Measurements on the Z Resonance with the L_3 Detector,* KUN, 1993.
10. A.A. Syed, *Particle Correlations in Hadronic Decays of the Z Boson,* KUN, 1994.
11. R.J.A.P. Rosmalen, *A test of QED with $e^+e^- \rightarrow \gamma\gamma$ at LEP energies,* KUN, 1994.
12. P. Vikas, *J/ψ Production and Decay at the Z Resonance,* UU, 1994.
13. D. Zhang, *Muon Pair Production in e^+e^- Collisions at the Z Resonance,* UvA, 1994.
14. H.G. Raven, *Measurement of Invisible Z Decays,* UU, 1995.
15. B.C.C. van der Zwaan, *Experimental Study of Mixing and Assymmetry in* $Z \rightarrow b\bar{b}$, KUN, 1995.
16. M.P. IJzerman, *Study of Neutral Current Coupling Constants from Tau Pair Production,* KUN, 1996.
17. E.N. Koffeman, *A luminosity measurement at LEP using the L3 detector,* KUN, 1996.
18. H.P. Kuijten, *Measurement of Hadronic Cross Sections and Asymmetries on the Z-Resonance,* KUN, 1996.
19. A.O. Buytenhuijs, *QCD Gluon Radiation Studies Using the L3 Detector,* KUN, 1996.
20. S. Chekanov, *Local Multiplicity Fluctuations and Intermittent Structure inside Jets,* KUN, 1997.
21. W. van Rossum *Hadron production in two-photon collisions at LEP,* UU, 1998.
22. A.P. Colijn, *Measurement of the Tau Lepton Lifetime,* UvA, 1999.
23. W.C. van Hoek, *Excited Beauty at L3,* KUN, 1999.
24. T. van Rhee, *Charmonium Formation in Two-Photon Collisions,* UU, 2000.
25. A.J.W. van Mil, *Cosmic-Ray Muons in the L3 Detector,* KUN, 2001.
26. A.J.M. Muijs, *Tau Pair Production above the Z Resonance,* KUN, 2001.
27. R.C.W. van Gulik, *Resonance production in two-photon collisions,* UL, 2001.
28. J.A. van Dalen, *Bose-Einstein Correlations in e^+e^- Events,* KUN, 2002.
29. D.J. Mangeol, *Correlations in the Charged-Particle Multiplicity Distribution,* KUN, 2002.
30. M.P. Sanders, *Pion (Non-) Correlations in Hadronic Events at the Z Resonance,* KUN, 2002.
31. B.G. Petersen, *Tau cosmic ray induced muon spectrum measured with the L_3 detector,* KUN, 2002.
32. Y. Hu, *Search for the Standard Model Higgs Boson and Study of the Scaling Property of QCD Dynamical Fluctuations at LEP,* KUN, 2002.
33. D.N. van Dierendonck, *Measurements of the W-pair production rate and the W mass using four-jet events at LEP,* UvA, 2002.

34. H.G.S. Wilkens, *Experimental study of high energy muons from Extensive Air Showers in the energy range 100 TeV to 10 PeV*, KUN, 2003.

35. M. Dierckxsens, *Measurement of Triple Gauge-Boson Couplings in* e^+e^- *Collisions at LEP,* KUN, 2004.

There are four additional theses expected.

Appendix B

Publications

The results of both the L3 and DELPHI experiments have resulted in a large number of publications in leading scientific journals. The following lists are not complete, as both collaborations will continue to publish results in the coming few years.

DELPHI

1. F. Stichelbaut *et al.*, “Performance Of The Delay Lines Of The Delphi Forward Muon Chambers,” Nucl. Instrum. Meth. A **283** (1989) 792.
2. P. A. Aarnio *et al.*, “Measurement Of The Mass And Width Of The Z0 Particle From Multi - Hadronic Final States Produced In E+ E- Annihilations,” Phys. Lett. B **231** (1989) 539.
3. P. A. Aarnio *et al.*, “Study Of Hadronic Decays Of The Z0 Boson,” Phys. Lett. B **240** (1990) 271.
4. P. A. Aarnio *et al.*, “Study Of The Leptonic Decays Of The Z0 Boson,” Phys. Lett. B **241** (1990) 425.
5. P. Abreu *et al.*, “A Precise Measurement Of The Z Resonance Parameters Through Its Hadronic Decays,” Phys. Lett. B **241** (1990) 435.
6. P. Abreu *et al.*, “Search For Heavy Charged Scalars In Z0 Decays,” Phys. Lett. B **241** (1990) 449.
7. P. Abreu *et al.*, “Search For The T And B-Prime Quarks In Hadronic Decays Of The Z0 Boson,” Phys. Lett. B **242** (1990) 536.
8. P. Abreu *et al.*, “Search For Light Neutral Higgs Particles Produced In Z0 Decays,” Nucl. Phys. B **342** (1990) 1.
9. P. Abreu *et al.*, “Search For Pair Production Of Neutral Higgs Bosons In Z0 Decays,” Phys. Lett. B **245** (1990) 276.
10. P. Abreu *et al.*, “Search For Scalar Quarks In Z0 Decays,” Phys. Lett. B **247** (1990) 148.
11. P. Abreu *et al.*, “A Study Of Intermittency In Hadronic Z0 Decays,” Phys. Lett. B **247** (1990) 137.
12. P. Abreu *et al.*, “A Search For Sleptons And Gauginos In Z0 Decays,” Phys. Lett. B **247** (1990) 157.
13. P. Abreu *et al.*, “A Comparison Of Jet Production Rates On The Z0 Resonance To Perturbative QCD,” Phys. Lett. B **247** (1990) 167.
14. P. Abreu *et al.*, “Energy-Energy Correlations In Hadronic Final States From Z0 Decays,” Phys. Lett. B **252** (1990) 149.

15. P. Abreu *et al.*, "Measurement Of The Partial Width Of The Decay Of The Z0 Into Charm Quark Pairs," Phys. Lett. B **252** (1990) 140.

16. P. A. Aarnio *et al.*, "The Delphi Detector At Lep," Nucl. Instrum. Meth. A **303** (1991) 233.

17. P. Abreu *et al.*, "Charged Particle Multiplicity Distributions In Z0 Hadronic Decays," Z. Phys. C **50** (1991) 185.

18. P. Abreu *et al.*, "Experimental Study Of The Triple Gluon Vertex," Phys. Lett. B **255** (1991) 466.

19. P. Abreu *et al.*, "Search For Low Mass Higgs Bosons Produced In Z0 Decays," Z. Phys. C **51** (1991) 25.

20. P. Abreu *et al.*, "Charged Particle Multiplicity Distributions In Restricted Rapidity Intervals In Z0 Hadronic Decays," Z. Phys. C **52** (1991) 271.

21. P. Abreu *et al.*, "A Study of the reaction e+ e- $\to$ mu+ mu- around the Z0 pole," Phys. Lett. B **260** (1991) 240.

22. P. Abreu *et al.*, "Study of orientation of three jet events in Z^0 hadronic decays using the DELPHI detector," Phys. Lett. B **274** (1992) 498.

23. P. Abreu *et al.*, "Determination of Z0 resonance parameters and couplings from its hadronic and leptonic decays," Nucl. Phys. B **367** (1991) 511.

24. P. Abreu *et al.*, "Search for excited charged leptons in Z0 decays," Z. Phys. C **53** (1992) 41.

25. P. Abreu *et al.*, "The reaction e+ e- $\to$ gamma gamma (gamma) at Z0 energies," Phys. Lett. B **268** (1991) 296.

26. P. Abreu *et al.*, "A Measurement of the lifetime of the tau lepton," Phys. Lett. B **267** (1991) 422.

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28. P. Abreu *et al.*, "A Search for neutral Higgs particles in Z0 decays," Nucl. Phys. B **373** (1992) 3.

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30. P. Abreu *et al.*, "Study of final state photons in hadronic Z0 decay and limits on new phenomena," Z. Phys. C **53** (1992) 555.

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38. P. Abreu *et al.*, "Determination of $alpha_s$ in second order QCD from hadronic Z decays," Z. Phys. C **54** (1992) 55.

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40. P. Abreu *et al.*, "Charged particle multiplicity distributions for fixed number of jets in Z0 hadronic decays," Z. Phys. C **56** (1992) 63.

41. P. Abreu *et al.*, "Measurement of the partial width of the Z0 into b anti-b final states using their semileptonic decays," Z. Phys. C **56** (1992) 47.

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48. P. Abreu *et al.*, "A Search for lepton flavor violation in Z0 decays," Phys. Lett. B **298** (1993) 247.

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122. P. Abreu *et al.*, “Mean lifetime of the B(s)0 meson,” Z. Phys. C **71** (1996) 11.

123. P. Abreu *et al.*, "First study of the interference between initial and final state radiation at the Z resonance," Z. Phys. C **72** (1996) 31.

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131. P. Abreu *et al.*, "Search for neutralinos, scalar leptons and scalar quarks in e+ e- interactions at s**(1/2) = 130-GeV and 136-GeV," Phys. Lett. B **387** (1996) 651.

132. P. Abreu *et al.*, "Tuning and test of fragmentation models based on identified particles and precision event shape data," Z. Phys. C **73** (1996) 11.

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