Chapter 8

The Number of Neutrinos and the Z Line Shape

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The Standard Theory can fit any number of fermion families, as long as the number of leptons and quark families are the same. At the time of the conception of LEP, the number of such families was unknown, and it was feared that the Z resonance would be washed out by decaying into so many families of neutrinos! It took only a few weeks in the fall of 1989 to determine that the number is three. The next six years (from 1990 to 1995) were largely devoted to the accurate determination of the Z line shape, with a precision that outperformed the most optimistic expectations by a factor of 10. The tale of these measurements is a bona fide mystery novel, the precession of electrons being strangely perturbed by natural phenomena, such as tides, rain, hydroelectric power, fast trains, not to mention vertical electrostatic separators. The number hidden in the loops of this treasure hunt was 179, the first estimate of the mass of the top quark; then, once that was found, where predicted, the next number was close to zero: the logarithm of Higgs mass divided by that of the Z. Twenty years later, the quality of these measurements remains, but what they tell us is different: it is no longer about unknown parameters of the Standard Theory, it is about what lies beyond it. This is so acutely relevant, that CERN has launched the design study of a powerful Z, W, H and top factory.

1. Introduction: What is the Number of Families of Fermions?

At the time LEP started, the basic properties of the weak interactions were already well known. One pressing question, however, could not be answered either by theoretical arguments or by direct experiments: what is the number of families of fermions? LEP answered this fundamental question in a few weeks by measuring the Z resonance. With six years of data and meticulous measurements of luminosity and energy the LEP experimentalists determined the Z boson mass and width, as well as the Z decay rates, with a precision which is unlikely to be surpassed soon.

All elementary quarks and leptons that have been observed are organised in *exactly* three families: (or generations).

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix} \quad \text{doublets of left-handed quarks}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \quad \text{singlets of right-handed quarks}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \text{doublets of left-handed leptons}$$

$$\begin{pmatrix} ?\nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} ?\nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} ?\nu_\tau \\ \tau \end{pmatrix} \quad \text{singlets of right-handed leptons}$$

As far as we can tell the Electroweak theory could not easily accomodate further isolated fermions, but it could accomodate any number of families of the same type. One could easily envisage a situation where many families including heavy charged quarks and leptons could exist, without these heavy leptons being ever produced in accessible experiments, by lack of available energy. Nevertheless, since the known neutrinos are very light, it is natural to expect that these additional families would include light neutrinos as well, leading to the possibility that many families of light neutrinos would exist.

The existence of many light neutrinos would have considerable cosmological consequences. In particular, the evolution of the universe within the first second after the Big Bang would be profoundly affected. The argument, developed in Ref. 1, is the following. At the time where energies are large enough, reactions such as $e^+e^- \rightarrow \nu\bar{\nu}$ transform a fraction of available energy into neutrinos in a democratic way. The creation of neutrons and protons however is controlled by reactions involving the electron neutrino, such as $\nu_e + n \rightarrow p + e^-$, and is consequently very sensitive to the number of light neutrino families, N_ν , which compete with electron neutrinos. The relative abundance of Hydrogen, Deuterium and Helium, and therefore the entire chemical constitution of our universe is a sensitive function of this number.

Before SLC and LEP started, limits on the number of light neutrinos were given from the above cosmological considerations, since there are data on the relative abundance of various nuclei in the universe, in particular the ratio of helium to hydrogen, or, with similar arguments, from the time development of the supernova 1987A. There were also indications from the direct search for the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ (single-photon experiments), or from the early measurements of the Z and W boson properties in the CERN and FERMILAB $p\bar{p}$ experiments. A review² of these constraints published in 1989 evaluated the best estimate of N_ν to be $N_\nu = 2.1^{+0.6}_{-0.4}$, and stated that “ $N_\nu = 3$ is perfectly compatible with all data, but four families still provide a reasonable fit”.

In searching for further families of neutrinos, it will be assumed that their couplings are the same as those of ν_e , ν_μ and ν_τ . Universality is deeply embedded in the Standard Theory, identical multiplets having the same coupling constant. It is very well verified for Charged Current interactions of e - μ - τ leptons, including the neutrinos, and for Neutral Current interactions of charged leptons.

2. Determination of the Number of Light Neutrino Species at LEP and SLC

The most precise determination of the number of light neutrino species is obtained from measurements of the visible cross-sections of e^+e^- annihilation at and around the Z resonance, as is made explicit in Fig. 1. If the Z is allowed to decay into more types of light neutrinos which will lead to an invisible final state, it will decay less often into the visible ones.

The realization that the visible cross-sections might be sensitive to the number of light neutrinos is rather ancient, one finds the question asked in John Ellis "Zedology",³ where one can find this anguished question: *The Z peak is large and*

Fig. 1. The $e^+e^- \rightarrow \text{hadrons}$ cross section as a function of center-of-mass energy. This curve was drawn before LEP start-up in 1987. At that time the Z mass was measured to be around 92 GeV with an error larger than 1.5 GeV. The dotted line represents the born approximation prediction for three species of light neutrinos. The full line includes the effect of initial state radiation. The dashed line represents the effect of adding one more type of light neutrino with the same couplings as the first three. It is clear from this picture that the cross-section at the peak of the resonance contains most of the information on the number of light neutrino species.

dramatic, as long as there are not too many generations of fermions. Is it conceivable that there might be so many generations as to wash out the Z peak? Since at that time the bound on the number of light neutrinos was very weak (about 6000), this certainly was a frightening possibility for those planning to build LEP! Dramatic also were the few first weeks of SLC and LEP operation where it was quickly realized that the Z peak was there indeed, large and dramatic, and that, alas, the number of light neutrinos was three.

There was intense competition between the SLC at SLAC (California, USA) and LEP at CERN (Switzerland). The two projects were with rather different in concept. LEP was build as the largest possible conventional e^+e^- storage ring, with a circumference of 27 km. This standard technique would ensure few surprises and and reliable high luminosity. SLC on the other hand, was the prototype of a new concept of accelerator, the linear collider; it was re-using the old Stanford linac, with improvements in the acceleration technique (SLED) and addition of arcs to bring e^+ and e^- in collisions, as well as of challenging positron source and damping rings.

The commissioning of SLC started in early 1987, and lead to a number of technical difficulties, not surprising in retrospect for such a new project. The first Z hadronic decay was produced on April 11 1989, and recorded in the MarkII detector. Luminosity was very low, a few $10^{-27}/\text{cm}^2/\text{s}$, leading to a few Z hadronic decays per day. With the LEP start-up advertised for the 14 of July, the time where SLC would hold the lead was going to be short, and intense. Nevertheless the SLC collaboration was able to collect a total of 106 Z decays by 24 July and submit a publication,⁴ where the Z mass was determined to be $M_Z = 91.11 \pm 0.23$ GeV, and the number of light neutrinos species $N_\nu = 3.8 \pm 1.4$.

LEP did not start collisions on 14 of July but on 13 August for one week. The high luminosity optics were however not yet commissioned and events came at a rate of 1 a day for the four experiments; this was not enough to make a measurement. Running resumed on 20 September with superconducting quadrupoles and in just three weeks, until 9 October, 3000 Zs were collected in each of the experiments. By 13 October, a seminar was organized at CERN where the four collaborations presented their first results,⁵⁻⁹ shown in Table 1. The day before, SLC had organized a public conference where updated results had been presented,⁹ based on 480 events. The “online average” of these results is also shown in Table 1, $N_\nu = 3.12 \pm 0.19$. The number of light neutrinos was three.

Following this important contribution, SLC was shaken by an earthquake on 24 October 1989, from which it took more than a year to recover, and then concentrated on polarized beam physics. LEP went on, to the end of 1989 and for 6 more years (1989 to 1995), each experiment collecting 4 million hadronic Z decays. With the final results now available, the number of light neutrinos determined to be $N_\nu = 2.9841 \pm 0.0083$,¹⁰ as will be illustrated on Fig. 4.

The early results were unexpectedly precise, and the precision of final ones exceed by a factor 100 the expectations that could be found in the studies preceding the

Table 1. First results from LEP and SLC on the Z mass and the number of light neutrino species, as published around 12 October 1989 (in order of submission to the journal).

Experiment	Hadronic Zs	Z mass (GeV)			N _ν		
MARKII	450	91.14	±	0.12	2.8	±	0.60
L3	2538	91.13	±	0.06	3.42	±	0.48
ALEPH	3112	91.17	±	0.05	3.27	±	0.30
OPAL	4350	91.01	±	0.05	3.10	±	0.40
DELPHI	1066	91.06	±	0.05	2.4	±	0.64
Average		91.10	±	0.05	3.12	±	0.19

Table 2. Numerical values of quantum numbers, Neutral Current couplings, and Z decay partial widths, for the four types of fermions, for hadrons and total width. The value of $\sin^2 \theta_w^{\text{eff}}$ is 0.2315.

f	I_{3f}	Q_f	g_{Af}	g_{Vf}	Γ_f (MeV)
ν	1/2	0	1/2	1/2	167
e	-1/2	-1	-1/2	-0.04	84
u	1/2	2/3	1/2	0.19	300
d	-1/2	-1/3	-1/2	-0.35	383
b	-1/2	-1/3	-1/2	-0.35	376
Hadrons = $u + d + c + s + b$	—	—	—	—	1740
Total for three neutrinos	—	—	—	—	2500
Total for four neutrinos	—	—	—	—	2670

start of LEP. Once the method is explained in more detail, it will become clear that the unexpected capacity of the experiments to perform precise measurement of hadronic cross-sections is the reason for this success.

3. Determination of the Z Line Shape Parameters

Around the Z pole, the $e^+e^- \rightarrow Z \rightarrow f\bar{f}$ annihilation cross-section is given by

$$\sigma_f = \frac{12\pi(\hbar c)^2}{M_Z^2} \frac{s\Gamma_e\Gamma_f}{(s - M_Z^2)^2 + s^2 \frac{\Gamma_Z^2}{M_Z^2}}, \quad (1)$$

which is a general formula for a spin one particle produced in e^+e^- annihilation into a visible channel f . This typical resonance shape peaks around the Z mass, $\sqrt{s} = M_Z$, and has a width Γ_Z . If the Z decays a fraction B_f of the time into a final state f the corresponding partial width is defined as $\Gamma_f = B_f\Gamma_Z$.

The Standard Theory predicts the numerical values for the Z partial widths, as displayed in Table 2. The main decay mode of the Z is into hadrons (70%), each of the leptons representing only 3% and three neutrinos would contribute 20%. There are no other substantial decay modes unless there are new particles. In particular the branching ratio into an hypothetical Higgs boson lighter than the Z is expected

to be very small. In this expression the number of neutrinos intervenes through the total Z width Γ_Z :

$$\Gamma_Z = 3\Gamma_\ell + \Gamma_{\text{had}} + N_\nu \Gamma_\nu. \quad (2)$$

If N_ν increases, the total width which is in the denominator of Eq. (1) increases, and the cross-section is decreased.

Equation (1) receives a number of modifications to account for the contribution of the photon exchange process (this is less than one percent), and more importantly what is called ‘initial state radiation’ (ISR), in which one or both of the initial state electrons lose energy into photons. This phenomenon reduces the initial state energy and smears out the resonance significantly as can be seen in Fig. 1. Due to the availability of calculations up to second order in perturbation theory, this large (30% at the peak) effect can be corrected for with a relative precision of 5×10^{-4} .

The principle of the analysis is then as follows: all visible channels are detected by large acceptance detectors and classified according to four categories: (i) hadrons, (ii) electron pairs, (iii) muon pairs, (iv) tau pairs. Examples of such events are shown in Fig. 2. These events are easy to detect, with high and well known efficiencies (as high as $99 \pm 0.05\%$ for hadronic decays), and to separate from each other.

In order to extract a cross-section from the number of events, the luminosity of the accelerator needs to be determined ($N = \mathcal{L} \cdot \sigma$). This is done by measuring at the same time another process with known cross-section, the elastic scattering $e^+e^- \rightarrow e^+e^-$, known as Bhabha scattering, which results in two low angle electron and positron. To this effect, the LEP experiments were equipped ab initio with low angle detectors, to detect these scattered electrons. The precision with which these detectors can measure this process is determined by the knowledge of the solid angle they cover and by the accuracy with which they measure the angle of the scattered electrons. The initial detectors were able to reach a precision of about one percent, but were progressively replaced with extremely precisely machined silicon tungsten calorimeters or silicon trackers (as in Fig. 3) which allowed a determination of the luminosity with an accuracy of 5×10^{-4} or better. It took many years of detailed higher order calculations to achieve a similar precision on the theoretical estimate of the cross-section within this well defined acceptance.

Measurements of cross-section for a given final state $f\bar{f}$ around the Z pole allow the extraction of three parameters: the position of the peak, the width of the resonance and an overall normalization, that is best obtained from the peak cross-section,

$$\sigma_f^0 = \frac{12\pi(\hbar c)^2}{M_Z^2} \frac{\Gamma_e \Gamma_f}{\Gamma_Z^2} = \frac{12\pi(\hbar c)^2}{M_Z^2} B_e \cdot B_f. \quad (3)$$

By measuring cross-sections for hadrons, electron pairs, muon pairs and tau pairs, one can obtain six numbers: the mass, the total width, and four other parameters which could be four branching ratios, or four partial widths. A better choice is to use the peak cross-section for hadrons $\sigma_{\text{had}}^{\text{peak},0}$, and the ratios of hadrons to the

Fig. 2. The four types of Z boson decays. Up left a decay into a pair of electrons, up right into a pair of muons, bottom left a pair of tau leptons, one decaying into an electron and the other into three particles, bottom right a pair of quarks that fragments into a number of hadrons.

various leptonic partial widths, $R_\ell \equiv \Gamma_{\text{had}}/\Gamma_\ell$. The Standard Theory implies lepton universality, and if this is assumed, the number of parameters can be reduced to four, $M_Z, \Gamma_Z, \sigma_{\text{had}}^{\text{peak},0}, R_\ell$. The choice of these observables to fit the line-shape measurements is dictated by the fact that they are experimentally uncorrelated, both from the point of view of statistical and systematic errors.

By reporting the expression for Γ_Z of Eq. (2) into the peak cross-section for hadrons, Eq. (3), the number of neutrinos can be extracted from quantities that are measured at the peak only:

$$N_\nu = \frac{\Gamma_\ell}{\Gamma_\nu} \cdot \left(\sqrt{\frac{12\pi R_\ell}{M_Z^2 \sigma_{\text{had}}^{\text{peak},0}}} - R_\ell - 3 \right). \quad (4)$$

The sensitivity of N_ν to R_ℓ is small, as there is a cancellation between the two terms containing this quantity. As a result the experimental measurement that enters most in the determination of N_ν is the peak cross-section, as already guessed intuitively

Fig. 3. Example of a LEP luminosity monitor (the L3 experiment). The process to be detected is elastic $e^+e^- \rightarrow e^+e^-$ scattering, shown on the left, which is seen by a coincidence of an electron in each of the detectors placed in the forward regions of the detector as shown on the right. In order to determine the solid angle seen by this coincidence in a way which is independent of the exact location of the collision point (which is difficult to determine) a set of two different acceptances is defined for the two arms. The precise definition of the acceptance is obtained by a precisely machined silicon telescope (SLUM) positioned in front of the electron calorimeters (luminosity monitor); there is a symmetric device on the other side of the detector.

from Fig. 1. This explains how quickly the number of neutrinos was obtained, a few weeks after the start-up of LEP and SLC.

4. Precision Measurements of the Mass and Width of the Z

The years 1990–1995, following this first success, were devoted to high-statistics, high-precision running of LEP at and around the Z pole. The LEP line shape results have been extensively documented in Ref. 10, in which the theoretical framework and all experimental results are described and combined.

The interest of precise measurements of the Z line shape parameters is evident when considering the Standard Theory expressions for the Z partial widths:

$$\Gamma_f = \frac{\alpha}{6\sin^2\theta_w\cos^2\theta_w} M_Z (g_{Lf}^2 + g_{Rf}^2) \cdot N_c \cdot \left(1 + \frac{3Q_f^2}{4} \frac{\alpha}{\pi}\right) (1 + \alpha_s/\pi + \dots), \quad (5)$$

where the couplings are given in a universal way by: $g_{L,R}f = I_{L,R}^3f - Q_f\sin^2\theta_w$, with $I_R^3f = 0$ for all known fermions. Equivalently one can define the coupling of the Z to the vector or axial vector fermion current:

$$\begin{aligned} g_{Vf} &= (g_{Lf} + g_{Rf}) = I_{Lf}^3 - 2Q_f\sin^2\theta_w, \\ g_{Af} &= (g_{Lf} - g_{Rf}) = I_{Lf}^3. \end{aligned} \quad (6)$$

Electroweak corrections to these formulae are largely accounted for by using universal effective couplings at the Z energy scale, both for $\alpha \rightarrow \alpha(M_Z^2)$ for the QED coupling constant, $\alpha_s \rightarrow \alpha_s(M_Z^2)$ for the strong coupling constant and for the weak mixing angle $\sin^2\theta_w \rightarrow \sin^2\theta_w^{\text{eff}}$; the so-called ρ parameter is introduced to account for the change in the relative strength of the neutral current and charged

Fig. 4. The $e^+e^- \rightarrow \text{hadrons}$ cross section as a function of center-of-mass energy, as measured by the LEP experiments. The curves represent the Standard Theory predictions for two, three and four species of light neutrinos. It is clear from this picture that there is no further light neutrino species with couplings identical to the first three.

current weak interactions, and normalize by a factor $\sqrt{\rho}$ all the couplings of eq. 6, and consequently all the Z partial widths.

These corrections amount to 6% for $\alpha(M_Z^2)$, and to 1–2% for $\sin^2 \theta_w^{\text{eff}}$ and ρ due to the large mass of the top quark. Small additional non-universal corrections (vertex corrections) amount to a few 10^{-3} ; they are insensitive to such effects as the top quark or Higgs boson masses. The b partial width constitutes the well known exception, the vertex correction involving the top quark amounting to 2%.

The interest of the various parameters extracted from the line shape is then schematically summarized as follows:

- The Z mass is one of the precise inputs to the electroweak theory calculations.
- The Z width is sensitive to the strong coupling constant and to the electroweak corrections involving the top quark mass. In two different ways: first, because of the strong top mass dependence of the ρ parameter; and in addition because 21.5% of hadronic Z decays are into b -quark pairs, it also acquires a sensitivity to the top mass from the b vertex correction.
- The peak cross-section for hadrons is very sensitive to the partial width of the Z into invisible modes, in particular N_ν and, in effect, to hardly anything else.
- The ratio of hadrons to leptons is very sensitive to the strong coupling constant $\alpha_s(M_Z^2)$, and to a lesser extent to the b vertex correction; the equality of the ratios for different lepton species constitute an essential test of the universality of the couplings of the Z boson.

By combination of these measurements one can obtain the most precise measurement of $\alpha_s(M_Z^2)$, and, more importantly at the time, a prediction for the mass of the top quark from radiative corrections. For instance the Z width varies by 2 MeV of the top quark mass varies by 10 GeV.

In 1992, searches for the top quark mass in high energy hadron colliders had not been successful yet. For this reason, there was great interest in performing precise measurement of the Z width. This can be done by measuring e^+e^- cross-sections across the Z resonance. The choice of points and the amount of running necessary at each point was subject to careful studies:¹¹

- The best scan would correspond to taking data at the peak, and at two points situated at +2 GeV and -2 GeV from the peak, with nearly equal amounts of data taken at each point.
- The beam energies were chosen so as to allow precise measurement of the LEP beam energies by the technique of resonant depolarization.

The resonant depolarization is a powerful technique which allows the determination of the beam energy in electron (and positron) storage rings, with precision of typically one part per million. So was measured in Novosibirsk the J/ψ mass $m = 3096.916 \pm 0.011$ MeV¹² and several other particles produced in e^+e^- annihilation. Beam polarization builds up slowly in the large storage ring (typically 5 hours rise time in the Z region), and requires exquisite beam orbit corrections. First observation of spin polarization was realized in 1990, by a small collaboration of accelerator and particle physicists¹³ and a first precise determination of the beam energy was performed by resonant depolarization in 1991.¹⁴ The method was determined to have an instantaneous precision of 100 KeV on the beam energy, as shown on Fig. 5(a).

To allow build up of the transverse polarization by Sokolov-Ternov effect, the energy had to be such that the spin tune was near a half-integer. By a lucky coincidence, the Z peak happens to correspond to $\nu = 103.5$.

It was thus decided to scan the Z peak at energies corresponding to spin tunes of 101.5, 103.5, 105.5. One unit of spin tune corresponding to 0.44065 GeV beam energy, or 0.8813 in center-of-mass energy, this is close enough to ± 2 GeV.

A very systematic scan of the Z resonance was performed in 1993, with regular energy calibrations of the LEP energies.

It was soon realized that the measurement of beam energy showed time variations at short time scale (a few hours) well beyond the intrinsic precision of the method. There began one of the most exciting sagas of the LEP era. The most evident effect was the effect of ground motion due to various effects, the most popular one being the earth tides.¹⁵ That a laboratory measurement of such scale could be associated with something as visible as the phase of the moon made great impact on the public! A precise measurement of the effect was undertaken at full moon on

Fig. 5. (a) Measurement of the LEP beam energy by resonant depolarization. The graph shows the ratio of polarization level before and after excitation by a small RF kicker oscillating at a frequency in the vicinity of the spin precession frequency. The lower horizontal axis shows the oscillation frequency reported in unit of the spin tune, while the top axis indicates the corresponding beam energy in MeV. (b) The LEP tide experiment. Measurement of the LEP beam energy by resonant depolarization were performed on a regular basis over 24 hours at full moon and compared with the calculation from the earth tides assuming elastic deformation.

11 November 1992 and the result is shown in Fig. 5(b) showing a rather significant swing of more than 10 MeV.

The Z width measurement is sensitive to relative point-to-point errors, and relatively safe against short term energy variations, given that the scan pattern of -2 , peak and $+2$ energy points was very well randomized by the running incidents of the accelerator. The Z mass, however, is sensitive to the absolute calibration of the beam energy.

It was realized in 1994 that the time evolution of the LEP energy was also disturbed by human activity. Jumps were observed during a long-term stability experiment, with a perplexing daily pattern. This may have biased the Z mass measurement, since, during the 1993 scan, the energy calibrations were always performed at the end of data taking periods of 8–10 hours. To monitor this effect, 16 NMR probes were inserted in a sample of the LEP magnets, to observe possible time variations. This should allow a complete study of these jumps, and a new scan was decided for 1995, in conditions similar to those of 1993, and additional monitoring. In 1994 data had been taken at the Z peak to accumulate large statistics.

As it turned out, the cause of the constant rise in the magnetic field was attributed to electric perturbations due to the passage of the french trains (TGV) in the area. This is shown in a spectacular way in Fig. 6. Due to hysteresis, this led to a positive drift of the beam energy during data taking and to a shift of about 3 MeV in the determination of the average beam energy. The corresponding correction

to the Z mass was somewhat larger than the quoted systematic error from the 1993 scan.

The LEP energy determination revealed many such effects and resulted in overall precision of 1.7 MeV systematic error on the Z mass and 1.1 MeV on the Z width, as described in several papers.^{16,17}

In addition to this careful determination of the LEP energies, it was necessary to ensure high precision for the experimental determination of the cross-sections, with particular attention to possible energy-dependent errors. High statistics were by then available, each experiment collecting around one million events. Major sources of systematic errors on the determination of the Z mass and width are:

- The contamination of the Z decays by non-resonant backgrounds, which tend to widen the apparent shape of the peak.
- The fact that the effect of initial-state radiation is not the same above the peak, where it is dominated by emission of a photon back to the Z peak, and below, where its effect is essentially to reduce the visible cross-section.

Figure 4 highlights the precision of the final LEP data.

5. The Discovery of the Top Quark, the Higgs Boson Mass

After the 1993 Z peak scan, the LEP experiments were able to produce for the 1994 winter conferences a combined measurement of the Z width with a precision of 3 MeV, which was the main ingredient to a prediction¹⁸ of the top quark mass of 172^{+13+18}_{-14-20} (the first error corresponds to the experimental error, the second one to the unknown mass of the Higgs boson). A month later, the first indicative observations of the top quark with a mass of 176 ± 16 GeV were announced by the CDF collaboration¹⁹ at the Fermilab Tevatron proton-antiproton collider! The discovery of the top quark was made officially²⁰ one year later in 1995.

As soon as the top quark was discovered, a large unknown was removed from the interpretation of the precision measurements. As a consequence, these measurements could be turned into predictions of the Higgs boson mass. The Higgs boson sensitivity of the Electroweak Radiative Corrections scales as $\frac{\alpha}{\pi} \cdot \log(\frac{m_h}{m_Z})^2$, and a precise determination of the Higgs boson mass (should it exist) is difficult, however the last result from the Z line shape as given in¹⁰ was $m_h = 129 + 74 - 49$ GeV.

6. Discussion and Outlook

It took several years of analysis by the LEP experimenters to extract the final values of the Z line shape parameters documented in Ref. 10 from which all precise numbers, statistical correlations, etc. should be taken. In the end, the Z mass was measured with a precision of 2×10^{-5} , the Z width, peak cross-section and ratio of hadrons to leptons to 10^{-3} , and the relative couplings of the various leptons

Fig. 6. The effect of trains on the LEP energy. The top plot shows the time variation of the voltage on the Geneva-Paris train track, the middle plot shows the voltage measured on the LEP beam pipe and the bottom plot shows the recorded NMR probe signal in the sampled LEP magnets.

to a precision of 2×10^{-3} . This precision exceeds the pre-LEP expectations by one order of magnitude. Such a precision, obtained after many years of hard work and clever tricks, was possible at LEP due to the extremely clean conditions, and the availability of resonant depolarization for the energy calibration in a circular machine. When LEP was closed in 2000, it was thought unlikely that, at least for the Z mass and width, these measurements would be improved in any foreseeable future.

Times have changed. The Higgs boson has been discovered at a mass of 125 GeV, and with it the Standard Theory in its minimal form is beautifully verified and

supposedly complete. As far as Radiative corrections are concerned, it can be said that “The Standard Theory has nowhere to go”, the predictions for the relations between e.g. the Z and W boson masses being now fixed, up to the precision of the calculations. This places particle physics in a new situation: the Standard Theory does not explain a number of well established experimental facts among which:

- the neutrino masses — discovery of the neutrino oscillations in 1998 implies that neutrinos have mass. This in turn almost certainly leads to the existence of the right-handed neutrinos.
- dark matter — the long standing astronomical observation of velocity of stars in galaxies requires matter that we cannot see, either weakly interacting (such as the popular Lightest Supersymmetric Particle should Supersymmetry be realized at relatively low energy (100 TeV or less) scale) or interacting even less, like right-handed neutrinos, or axions.
- the existence of a complete baryon-antibaryon asymmetry in the Universe — albeit with a small matter content. This points to a source of CP violation in excess of that present in quarks, and to the existence of matter-antimatter transitions.

The precision measurements of electroweak quantities were able to predict successfully the top mass, then the Higgs boson mass. Now that these particles are well known they could be used to test the existence of further weakly interacting particles or the existence of non-standard mechanisms for the Electroweak symmetry breaking. In addition the question of the existence of the right handed neutrinos, who can acquire mass not only from Yukawa couplings (Dirac terms) like all other fermions, but also from a Majorana mass term triggering the ‘see-saw’ mechanism, is a very open problem. Their mass can extend from a few eV up to the GUT scale.

In front of this very open field the experimental means of investigation should be as broad as possible. One of the tools of choice in this endeavor is the Future Circular Collider. In 2011, while the first evidence for the Higgs boson at the LHC^{22,23} was reported by ATLAS and CMS, with a mass of 125 GeV, shown on 13 December 2011 at CERN, it was pointed out that a circular e^+e^- collider of the new generation with the improvements developed for the b -factories could be built in the LEP/LHC tunnel to measure precisely the properties of this new particle.²⁴ There are serious issues with installing a new accelerator in the LHC, however, and the proposal was quickly modified to a grand scenario involving the construction of a new 100 km tunnel around Geneva, able to host in succession a high luminosity e^+e^- collider (dubbed TLEP then FCC-ee) and a 100 TeV superconducting collider (dubbed FCC-hh).

A first look at the physics that can be achieved in the FCC-ee has been published in Ref. 25. Considerable improvements can still be made on the Z line shape measurements given the huge luminosity of the future accelerator, and are discussed in that paper. To give an idea, Z mass and width measurement with a precision of

better than 100 KeV (yes, keV), can be envisaged, a measurement of the W mass to 500 keV, $\alpha_s(m_Z)$ with a precision of ± 0.0001 and $\alpha_{\text{QED}}(m_Z)$ with a precision of $\pm 210^{-5}$. More recent updates concerning the search for right-handed neutrinos can be found in²⁶ and for the top quark measurements in Ref. 27.

The combination of the FCC-ee and the FCC-hh, which are highly complementary, constitutes the most powerful means of investigation into the unknown that seems conceivable today. CERN has launched the FCC study,²⁸ with the aim of producing a conceptual design report in 2018, in view of offering an ambitious post-LHC accelerator project.

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