Z physics

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Abstract

This article describes the properties of the Z boson. Updated precision measurements from e^+e^--annihilation at the Z resonance are discussed as well as new results obtained above the Z pole. Measurements of Z pair production and associated production of Z boson with one or two photons are also reported. The analysis of these measurements constitutes an experimental test of the Standard Model and leads to an estimate and an upper limit for the mass of the Higgs boson.

1. Introduction

In the last decade the properties of the Z boson, its mass, total and partial decay widths as well as the couplings to fermions, have been measured to very high accuracy in e^+e^--collisions at the LEP and SLC colliders. These measurements allow precision tests of the Standard Model of Electroweak Interactions (SM) [?] and with other experimental data (e.g. W boson mass) allows to predict the mass of Higgs boson.

This article is organized as follows: Section 2 reviews the current status of precision measurements at the Z resonance from LEP and SLD. The production of fermion pairs in e^+e^--collisions above the Z resonance studied at LEP is described in section 3. Studies of the production of neutral bosons, the photon and the Z, are presented in section **??** together the derived limits on hypothetical self-couplings. Precision electroweak measurements are used in the SM framework to test the model and to estimate the mass of the Higgs boson (section **??**).

2. Measurements at the Z resonance

2.1. The lineshape of the Z boson

The 17 million Z decays collected by the four LEP experiments allowed high precision measurements at the permille level of total cross section forward-backward asymmetry [?] of the following channels:

$$\begin{aligned} e^+e^- &\to \text{hadrons}\,, \qquad e^+e^- \to e^+e^-\,, \\ e^+e^- &\to \mu^+\mu^-\,, \qquad e^+e^- \to \tau^+\tau^-\,. \end{aligned} \tag{1}$$

The increased LEP center-of-mass energy, $\sqrt{s}$ up to 200 GeV completed the scenario of two fermion production mediated by γ and Z and by their interference γZ. In Fig. 1 is shown a complete overview for $\mu\mu$ final state. The data are compared to the results of fits performed to extract the Z parameters [?] as for example: mass, m_Z, and width, Γ_Z. To perform these measurements with such accuracy some highly performing ingredients are necessary: precise theoretical calculations with the corresponding programs (ZFITTER,TOPAZ0) [?] and accurate (10^{-5}) LEP beam energy calibration [?]. An important improvement is the reduction of the theoretical error to $0.6\cdot10^{-3}$ [?] on the cross section of low angle Bhabha scattering, used by the LEP experiments to determine the luminosity.

From the measurements of total cross sections and forward-backward asymmetries the experiments determine nine parameters of Z boson. These parameters are the mass and total width of the Z, the hadronic pole cross section, σ^0_had, and for the three charged leptons the ratios of hadronic to leptonic widths, R_ℓ, and the pole asymmetries, $A_\mathrm{FB}^{0,\ell}$:

$$\begin{aligned} \sigma^0_\mathrm{had} &= \frac{12\pi}{m_\mathrm{Z}^2}\frac{\Gamma_\mathrm{e}\Gamma_\mathrm{had}}{\Gamma_\mathrm{Z}^2}\,, \quad R_\ell = \frac{\Gamma_\mathrm{had}}{\Gamma_\ell}\,, \\ A_\mathrm{FB}^{0,\ell} &= \frac{3}{4}A_\mathrm{e}A_\ell\,, \quad A_\ell = \frac{2\bar{g}_\mathrm{V}^\ell\bar{g}_\mathrm{A}^\ell}{(\bar{g}_\mathrm{V}^\ell)^2+(\bar{g}_\mathrm{A}^\ell)^2}\,. \end{aligned} \tag{2}$$

The effective vector- and axial-vector coupling constants, $\bar{g}_\mathrm{V}^\ell$ and $\bar{g}_\mathrm{A}$ are combined to give A_ℓ, the polarization parameter. The combined results of all four experiments lead to the results shown in Tab. 1. The LEP energy calibration contributes by 1.7 MeV and 1.3 MeV to the errors on m_Z and Γ_Z [?].

Fig. 2 compares the contours in the $A_\mathrm{FB}^{0,\ell} - R_\ell$ plane for the three lepton species. The three contours agree and assuming lepton universality yields:

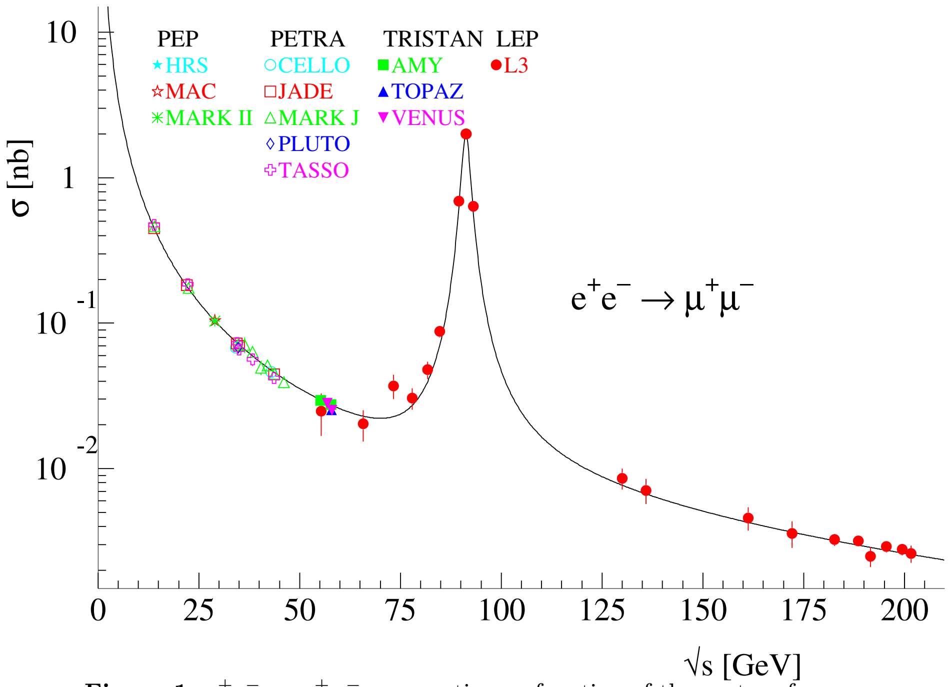

Figure 1. $e^+e^- \to \mu^+\mu^-$ cross section as function of the centre-of-mass energy.

m_Z	$91\,187.2 \pm 2.1$ MeV
Γ_Z	$2\,499.4 \pm 2.4$ MeV
$\sigma^0_{\rm had}$	41.544 ± 0.037 nb
$R_{\rm e}$	20.803 ± 0.049
R_μ	20.786 ± 0.033
R_τ	20.764 ± 0.045
$A^{0,{\rm e}}_{\rm FB}$	0.0145 ± 0.0024
$A^{0,\mu}_{\rm FB}$	0.0167 ± 0.0013
$A^{0,\tau}_{\rm FB}$	0.0188 ± 0.0017

Table 1. Combined result of the fits to nine parameter (Eq. 2) of the four LEP experiments.

$$\begin{aligned} R_\ell &= 20.768 \pm 0.024 \;, \\ A^{0,\ell}_{\rm FB} &= 0.01701 \pm 0.00095 \;. \end{aligned} \tag{3}$$

The measurements are in agreement with the SM expectation for a light Higgs boson.

At this point, the decay width of Z boson in hadrons and charged lepton can be derived:

$$\begin{aligned} \Gamma_{\rm had} &= 1743.9 \pm 2.0 \text{ MeV} \;, \\ \Gamma_\ell &= 83.959 \pm 0.089 \text{ MeV} \;. \end{aligned}$$

Subtracting the leptonic and hadronic width from the total, it is possible to derive the fraction of Z decays into invisible particles, as neutrinos.

$$\begin{aligned} \Gamma_{\rm inv} &= \Gamma_Z - \Gamma_{\rm had} - 3\,\Gamma_\ell, \\ \Gamma_{\rm inv} &= 498.80 \pm 1.5 \text{ MeV} \;. \end{aligned} \tag{4}$$

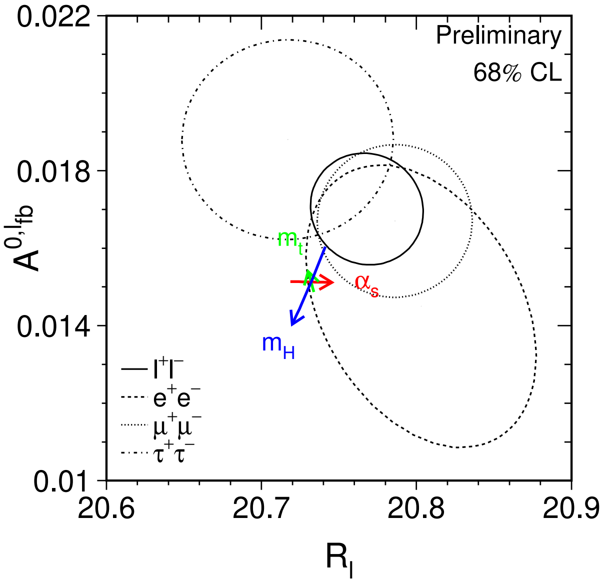

Figure 2. Contours in the $A^{0,\ell}_{\rm FB}$-R_ℓ plane for the three charged leptons obtained from the combination of the four LEP experiments. The solid line shows the result assuming lepton universality. The lines with arrows correspond to the variation of the Standard Model prediction when $m_{\rm H}$,$m_{\rm t}$ and $\alpha_{\rm s}$ are varied .

From the invisible width it is possible derive the number of neutrino families according to:

$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)^{\rm SM} = 2.9835 \pm 0.0083 \;. \tag{5}$$

This value, by two standard deviation lower than

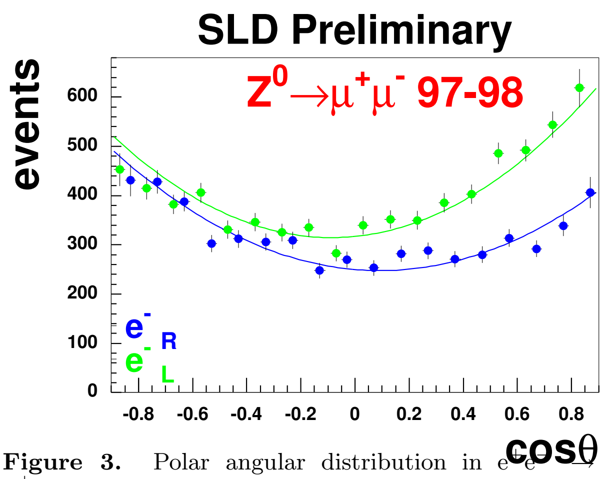

Figure 3. Polar angular distribution in $e^+e^- \to \mu^+\mu^-$ for left-and right-handed incoming electron are measured SLD.

the expected, is due mainly to the new measurement of hadronic pole cross,$\sigma^0_{\rm had}$.

If the SM neutrino families are three, it is possible derive an upper 95% CL limit on the Z decay width into other, non-standard invisible particles of $\Delta\Gamma_{\rm inv} < 2.0$ MeV.

2.2. Couplings of the Z to charged leptons

Exploiting the unique feature of a high degree of polarization of the electron beam at SLC e^+e^--collider, it is possible to measure precisely the couplings of the electron. This is obtained from the relative difference of total cross sections at the Z for left- and right-polarized incoming electrons, $A_{\rm LR} = (\sigma_{\rm e_L} - \sigma_{\rm e_R})/(\sigma_{\rm e_L} + \sigma_{\rm e_R}) = A_{\rm e}$,

Based on 550 000 $e^+e^- \to$ hadrons events collected by the SLD experiment the value of $A_{\rm e}$ [**?**] is measured:

$$A_{\rm e} = 0.1514 \pm 0.0022\,. \qquad (6)$$

The lepton pair polar angle distributions lead to the measurements of the polarization parameter of the three charged leptons, as shown in Fig.3, observed for different polarizations of the colliding electrons [?], as summarized in Tab. 2.

Combining the measurements of the hadronic left-right asymmetries and the determinations of A_ℓ in the leptonic channels yields the most precise measurement of the effective weak mixing angle [?]:

$$\sin^2\overline{\vartheta}_{\rm W} = \frac{1}{4}\left(1 - \frac{\bar{g}^\ell_{\rm V}}{\bar{g}^\ell_{\rm A}}\right) = 0.23097 \pm 0.00027\,. \quad (7)$$

At LEP, from tau lepton decay it is possible to extract more information on the coupling of the τ

$A_{\rm e}$	0.1548 ± 0.0058
A_μ	0.142 ± 0.015
A_τ	0.140 ± 0.015
A_ℓ	0.1514 ± 0.0021

Table 2. Measurements by the SLD experiment of the polarization parameter from leptonic and combined for three lepton species left-right forward-backward asymmetries.

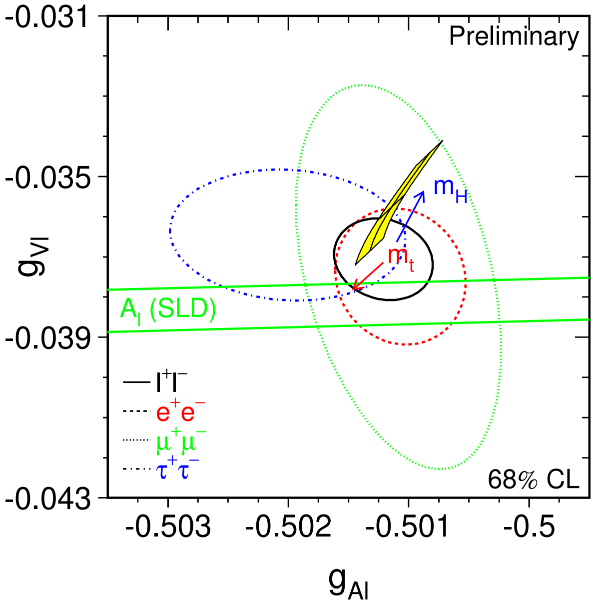

Figure 4. Contours of 68% probability in the $\bar{g}^\ell_{\rm V}$,$\bar{g}^\ell_{\rm A}$ plane from LEP and SLD measurents. The solid line represents the combined contour assuming lepton universality. The shaded area corresponds to the SM expectations, with arrows pointing in the direction of increasing the Higgs and top masses.

and the electron to the Z. The τ polarization can be derived from the informations carried from its decay products, as energy and decay angles [**?**]. Then, from the dependence of the polarization from polar angle it is possible to extract $A_{\rm e}$, A_τ:

$$\mathcal{P}_\tau(\cos\theta) \quad = \quad \frac{(1+\cos^2\theta)\,A_\tau + 2\cos\theta\,A_{\rm e}}{(1+\cos^2\theta) + 2\cos\theta\,A_\tau A_{\rm e}}$$

Combined results of the experiments are [?]:

$$A_{\rm e} = 0.1483{\pm}0.0051\,, \quad A_\tau = 0.1425{\pm}0.0044\,. \quad (8)$$

In Fig. 4 the measurements of the effective coupling constants of the three leptons at LEP and SLD are compared to the SM prediction. In

	b-quark	c-quark
$R_{\rm q}$	0.21642 ± 0.00073	0.1674 ± 0.0038
$A_{\rm FB}^{0,{\rm q}}$	0.0988 ± 0.0020	0.0692 ± 0.0037
$A_{\rm q}$	0.911 ± 0.025	0.630 ± 0.026

Table 3. Results of a common fit to measurements of Z decays into b- and c-quarks at LEP and SLD.

	LEP & SLD	SM
A_ℓ	0.1497 ± 0.0016	$0.1431\,^{+0.0054}_{-0.0057}$
$A_{\rm b}$	0.892 ± 0.016	0.935
$A_{\rm c}$	0.625 ± 0.021	0.668

Table 4. Determination of the polarization parameter of b- and c-quarks from measurements at LEP and SLD. The rightmost column contains the SM preditions.

conclusion all measurements are in agreement with the SM for a light Higgs boson mass.

At this point, it is possible test the lepton couplings in the neutral sector:

$$
\begin{aligned}
\bar{g}_{\rm V}^{\mu}/\bar{g}_{\rm V}^{\rm e} &= 0.946 \pm 0.065\,,\\
\bar{g}_{\rm V}^{\tau}/\bar{g}_{\rm V}^{\rm e} &= 0.955 \pm 0.030\,,\\
\bar{g}_{\rm A}^{\mu}/\bar{g}_{\rm A}^{\rm e} &= 1.0002 \pm 0.0013\,,\\
\bar{g}_{\rm A}^{\tau}/\bar{g}_{\rm A}^{\rm e} &= 1.0019 \pm 0.0015\,. \qquad (9)
\end{aligned}
$$

This result is nicely consistent with the lepton universality hypothesis. Then, imposing this it is possible derive the effective vector- and axial-vector couplings of charged leptons to the Z are measured at LEP and SLD to be:

$$
\begin{aligned}
\bar{g}_{\rm V}^{\ell} &= -0.03772 \pm 0.00041\,,\\
\bar{g}_{\rm A}^{\ell} &= -0.50117 \pm 0.00027\,. \qquad (10)
\end{aligned}
$$

2.3. Couplings of the Z to quarks

For b- and c-quarks it is possible as for leptonic final state to measure: the total cross section, expressed in terms of ratios of partial decay widths to the hadronic width, $R_{\rm q} = \Gamma_{\rm q}/\Gamma_{\rm had}$, forward-backward pole asymmetries and the polarization parameters,$A_{\rm q}$, from the left-right forward-backward asymmetry. Also in this case these quantities depend from effective axial and vector coupling constants. The results of the four LEP experiments and SLD are combined. Tab. 3 presents the result of this combination [?]. The measurements of $R_{\rm b}$ and $R_{\rm c}$ are now in good agreement with the SM predictions (Fig. 5).

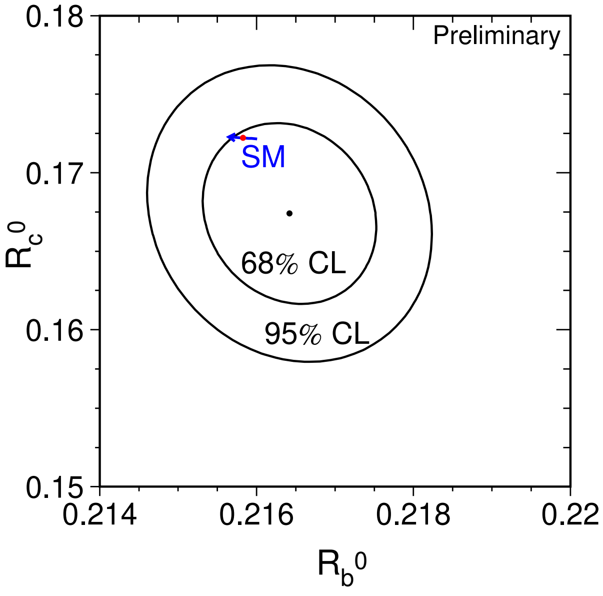

Figure 5. Contours in the $R_{\rm c}$-$R_{\rm b}$ plane obtained from combining the measurements at LEP and SLD. The arrow indicates the SM prediction as a function of the top quark mass.

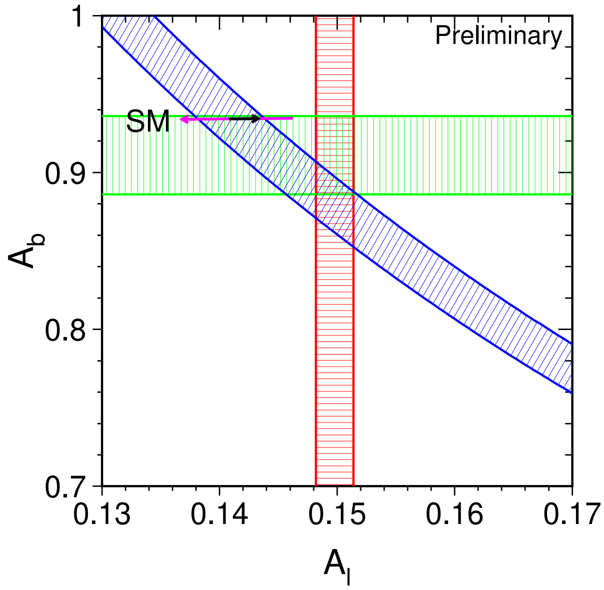

Figure 6. Comparison of the $A_{\rm b}$ measurement of SLD (horizontal band), the combined LEP and SLD result on A_ℓ (vertical) and the b-quark forward-backward asymmetry measured at LEP (sloping).

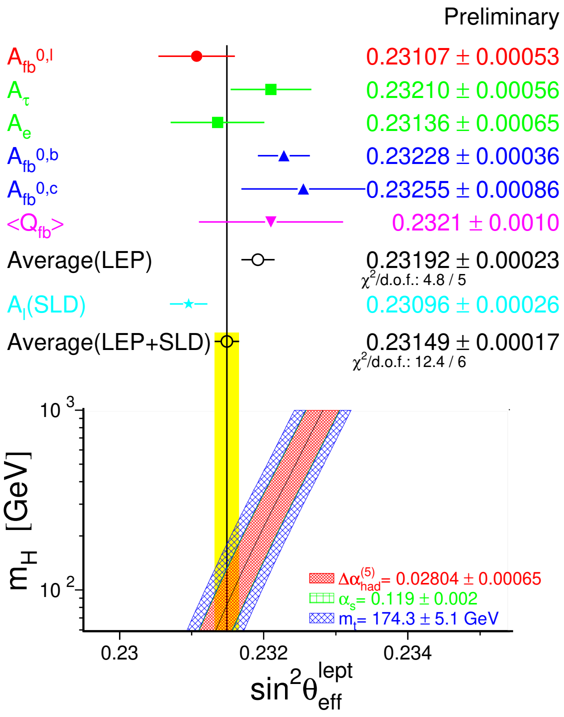

Figure 7. The effective weak mixing angle $\sin^2\overline{\vartheta}_\mathrm{W}$ derived from various measurements at LEP and SLD. At the bottom the SM prediction is shown as a function of the Higgs boson mass. The band represent the uncertainty due to m_t and the contribution of the five light quarks to the running of α (see the bands).

Year	$\sqrt{s}$	$\int\mathcal{L}\,\mathrm{d}t$
1995	130 – 140 GeV	5 pb^{-1}
1996	161/172 GeV	21 pb^{-1}
1997	183 GeV	55 pb^{-1}
	130/136 GeV	7 pb^{-1}
1998	189 GeV	180 pb^{-1}
1999	192/202 GeV	240 pb^{-1}
2000	202/208 GeV	62 pb^{-1}

Table 5. Collected integrated luminosities by each experiment at various cms energies . For 2000 is given an indication of the integrated luminosities collected at time of the conference.

	N_ν
L3	3.05 ± 0.12
DELPHI	2.82 ± 0.17
L3 LEP I	3.00 ± 0.08
lineshape	2.9835 ± 0.0083

Table 6. Determination of the number of neutrino generations from the analysis of single photon events above the Z resonance ($\sqrt{s}$=189-202 GeV). The combined value (LEP II) is compared to the average result from similar analyses at the Z pole (LEP I) [?,?].

These results are based on the analysis of the full statistics. This discrepance of 2.7σ of the b-quark polarization parameter (Tab. 4) can be real deviations in the quantities containing A_b and A_c or coupling of the Z to b-quarks different from SM.

2.4. Measurements of the effective weak mixing angle $\sin^2\overline{\vartheta}_\mathrm{W}$

From the measured asymmetries at the Z , the effective weak mixing angle $\sin^2\overline{\vartheta}_\mathrm{W}$ can be derived (Fig. 7). Averaging all measurements yields:

$$\sin^2\overline{\vartheta}_\mathrm{W} = 0.23149 \pm 0.00017\,. \qquad (11)$$

3. Fermion-pair production above the Z resonance

3.1. Measurements of total cross sections and forward-backward asymmetries at LEP

In the last years the increased, LEP energy allowed the study of fermion pair production above the Z resonance (Tab. 5). However, the cross section at high energy is two orders of magnitude smaller. At these cms energies the initial state radiation plays an important role, because the fermion pair production can take place at lower effective center of mass energies, $\sqrt{s'}$. If for example, $\sqrt{s'} \approx m_\mathrm{Z}$, the annihilation cross section is very high ('return-to-the-Z'). Because of the different nature of these events produced, traditionally two sets of cross sections and forward-backward asymmetries are measured. For total sample and high energy sample $\sqrt{s'/s} > 0.85$, as shown in Fig.**??**.

3.2. Single photon events and the number of neutrino families

An interesting process that profits of the 'return-to-the-Z' is $\mathrm{e}^+\mathrm{e}^- \rightarrow \nu\bar{\nu}\gamma$. This process is characterized from a single photon in the detector. The number of neutrino families can be derived by these measurements. Tab. 6 shows the comparison of the results derived above Z resonance with those at the Z pole derived from Z line-shape. The precision of both measurements is comparable.

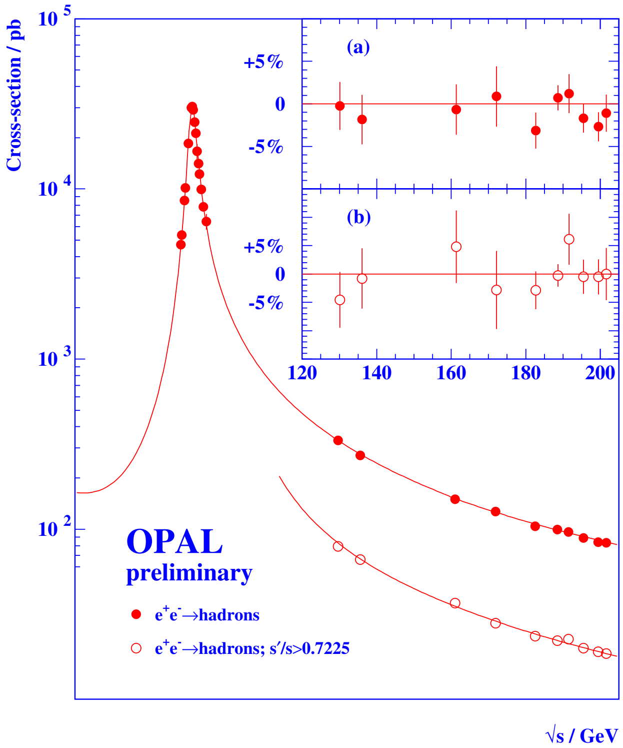

Figure 8. The cross sections for quark pair production as function of the cms energy measured by OPAL from the Z resonance up to 202 GeV. Above the Z resonance results for the inclusive and the high effective cms energy samples are shown and compared to the SM. [?]

3.3. γ/Z interference

At cms energies well above the Z resonance, the reduced importance of Z boson exchange allows the determination of γ/Z interference with high precision. At the Z pole the contribution from γZ interference to the cross section is small and cannot be determined accurately. Therefore, for the determination of Z parameters it is fixed to SM value. Using the high energy data, where γZ interference to the cross section is larger, this contribution can be measures much more precisely.

The L3 collaboration [**?**] has used the approach of S-Matrix to determine the contribution of γ/Z interference and Z boson exchange, thus reducing the number of theoretical assumptions. The lowest-order total cross section, $\sigma^0_{\rm tot}$ and forward-backward asymmetries, $A^0_{\rm fb}(s)$, can be written as:

$$\sigma^0_a(s) = \frac{4}{3}\pi\alpha^2\left[\frac{g^a_f}{s} + \frac{j^a_f(s-\bar{M_Z}^2)+r^a_f\, s}{(s-\bar{M_Z}^2)^2+\bar{M_Z}^2\bar{\Gamma_Z}^2}\right]$$

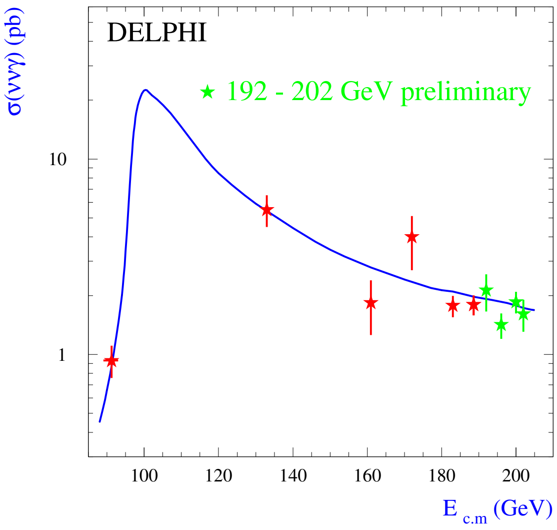

Figure 9. Cross section measurement $e^+e^- \to \nu\bar{\nu}\gamma$ above the Z resonance measured by DELPHI. [?]

for $a = {\rm tot}, {\rm fb}$,

$$A^0_{\rm fb}(s) = \frac{3}{4}\frac{\sigma^0_{\rm fb}(s)}{\sigma^0_{\rm tot}(s)},$$

$$\text{with} \quad \sigma^0_{fb} = \frac{4}{3}\left(\sigma_f - \sigma_b\right).$$

where the S-matrix parameters r_f,j_f and g_f give the Z exchange, γ/Z interference and photon contributions for fermions of type f. For hadronic final states the parameter $j^{\rm tot}_f$ are the sums over all produced quark flavours.

4. Production of neutral boson pairs at LEP

4.1. Production of Z-boson pairs

Since 1987 LEP is running at cms above the production threshold for Z-pair, $e^+e^- \to$ ZZ. In the SM this process is mediated by *t*- and *u*-channel exchange of an electron with two Feynman diagrams contributing in lowest order (Fig. **??**). The experimental investigation of ZZ production is made difficult by the rather low cross section, compared with competing processes that constitute large and sometimes irreducible backgrounds. Candidate events are selected as four-fermion final states requiring that the reconstructed invariant masses of jet and lepton pairs are consistent with the production of real Z bosons. The sum of the

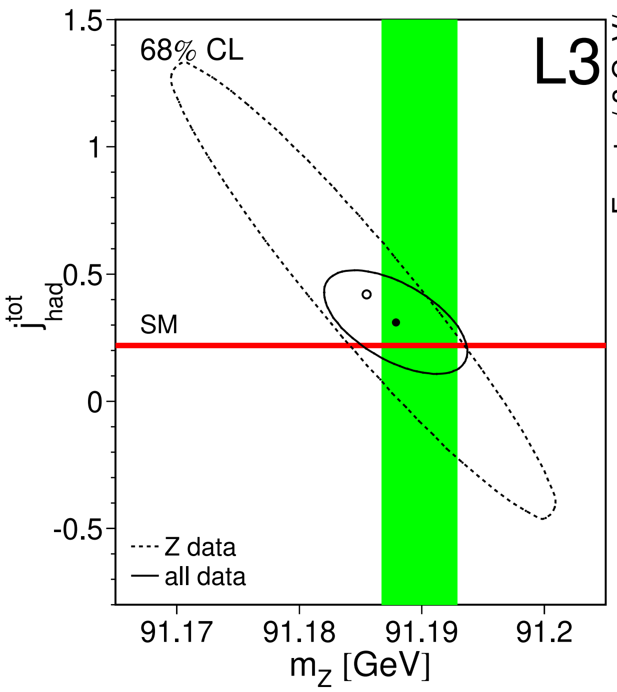

Figure 10. Contours plot in the m_Z, j_{had}^{tot} plane under the assumption of lepton universality. The dashed line is obtained from Z only data; the inclusion of 130 GeV to 189 GeV data gives the solid line. The circle (Z data) and cross (all data) indicate the central value of the fits. The Standard Model prediction for j_{had}^{tot} is shown as the horizontal band. The vertical band corresponds to 68% c.l. on m_Z assuming Standard Model value for γ/Z interference.

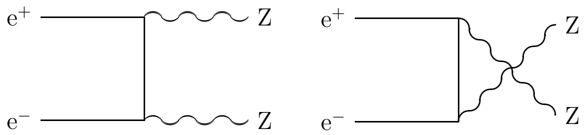

Figure 11. Feynman diagrams contributing to $e^+e^- \to$ ZZ at lowest order.

invariant mass of dilepton pair in candidate events of ALEPH collected at $\sqrt{s}$ up to 202 GeV is shown in Fig. **??**. The presence of a $e^+e^- \to$ ZZ signal is clearly visible in the data.

The ZZ cross sections measured at different cms are shown in Fig. **??** with the expected SM expectation. In the same illustration is shown also the ZZ $\to$ b$\bar{\text{b}}$ cross section.

The measurement of the b quark content in ZZ events [**?**] constitutes a test of the capabilities to identify an heavy particle decaying in b quarks

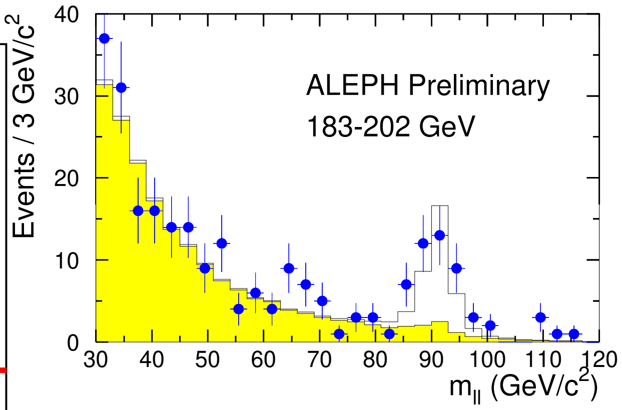

Figure 12. Distribution of the sum of the di-lepton masses in $e^+e^- \to$ ZZ candidates of ALEPH [?].

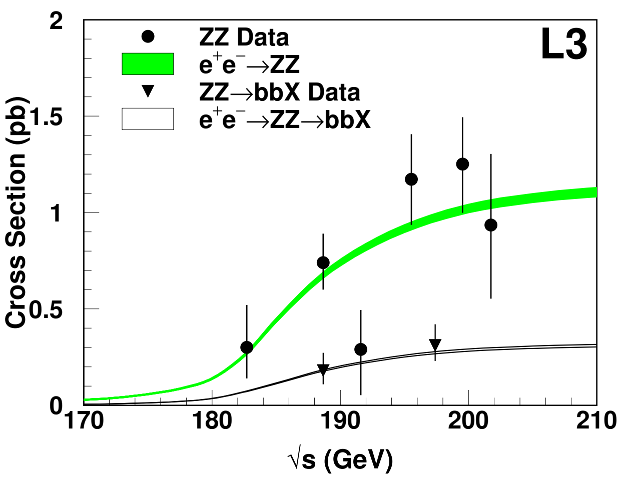

Figure 13. Standard Model prediction for $e^+e^- \to$ ZZ and ZZ $\to b\bar{b}X$ at various cms energies, as measured by L3, compared to the SM expectation.

recoiling against a Z boson. This configuration is of fundamental importance at LEP as it occurs in the production of Higgs boson.

4.2. Z-photon final states and limits on anomalous couplings

These results on Z-pair cross section can be also interpreted in terms of possible anomalous couplings among neutral gauge bosons, Fig. **??**. The most general parametrization of ZZZ and ZZγ anomalous coupling implies four complex parameters [**?**]: f_i^V, $V = \mathrm{Z}, \gamma$, $i = 4, 5$. At three level these couplings are zero in the SM and a possible non-zero value would change the ZZ cross

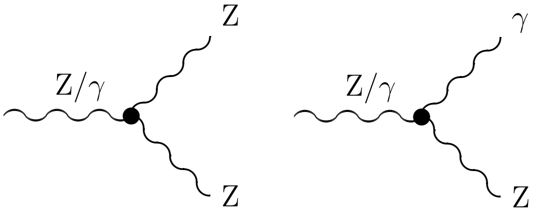

Figure 14. Anomalous couplings among neutral gauge bosons to be studies in Z-pair (left) and in Z-photon production (right).

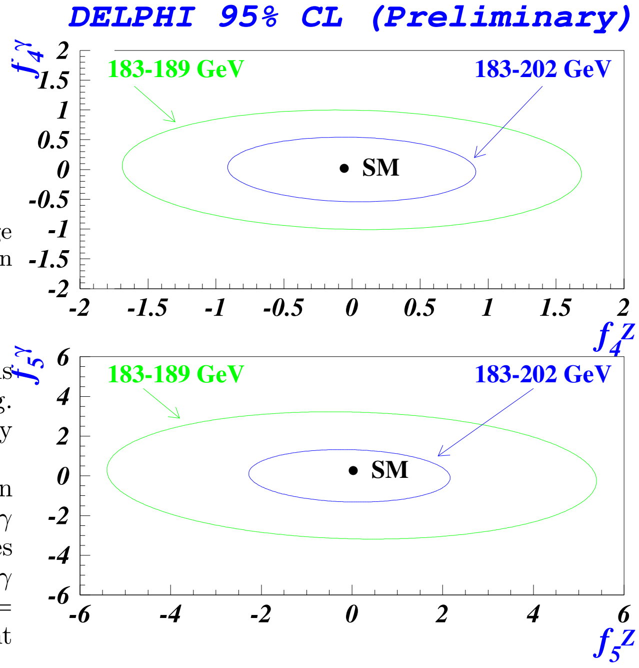

Figure 15. Region accepted at 95 % confidence level coupling f_5^V up to 202 SM expectaction are represented by points.

section and as well as the angular distributions and the invariant mass of decay products. In Fig. **??** the limits on two of these couplings put by DELPHI [**?**] are shown as contour plots.

More information on anomalous Z-photon couplings is extracted from analyses of $e^+e^- \to f\bar{f}\gamma$ (Fig. **??**) [**?**] and $p\bar{p} \to Z\gamma$ [**?**] events. In these cases eight parameters† are needed to describe the ZZγ and Z$\gamma\gamma$ vertices in a general way [?]: h_i^V; $V = \gamma, Z$, $i = 1, \ldots, 4$. These parameters are different and independent from those f_i^V already discussed.

At LEP rate and spectra of $e^+e^- \to$ hadrons $+\gamma$ and single photon events are analyzed. They are found to agree with the expectations as well as the study of Zγ events in $p\bar{p}$ collisions done by DØ .

A compilation of limits on Zγ coupling parameters is shown in Tab. **??**.

4.3. Z-photon-photon final states and limits on Anomalous Quartic Gauge Couplings

At these LEP cms energies the production of three bosons in final state as Z$\gamma\gamma$ is possible. Then is is possible to probe the Anomalous Quartic Gauge Boson Couplings (AQGC) [**?**]. In the SM the $e^+e^- \to Z\gamma\gamma$ process occurs by a radiation of photons from the incoming electron and/or positron, as shown in Fig. **??**. No QGC contribution is predicted at tree level and Z$\gamma\gamma$ events are hence sensitive to anomalous QGC effects.

This AQGC manifest themselves via deviation from SM cross section of this process and through a different shape in the least energetic photon spectrum.

The first measurement of this process at cms of 183 and 189 GeV has been performed by L3 Collaboration [**?**]. The measured cross section, based on a sample of $e^+e^- \to Z\gamma\gamma \to$ hadrons $+\gamma\gamma$ is presented in Fig. **??** with the expected evolution with $\sqrt{s}$ of SM cross section.

From a simultaneous fit to these variables the parameter a_0 and a_c describing the strenght of the AQGC and Λ representing the New Physics scale are derived:

$$-0.007 \text{ GeV}^{-2} < a_0/\Lambda^2 < 0.005 \text{ GeV}^{-2}$$

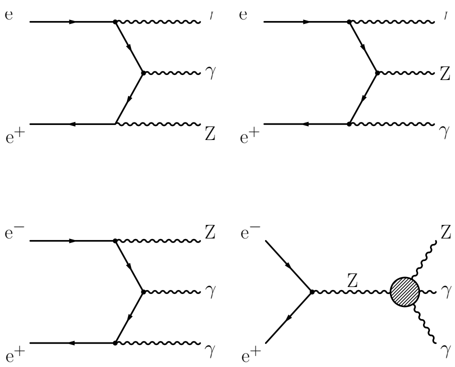

Figure 16. Three of the six SM contributing to $e^+e^- \to Z\gamma\gamma$. A possible QGC diagram is also shown.

† There is no constraint of two identical particles in the final state as in $e^+e^- \to ZZ$. Also, the f_i^γ and h_i^Z parametrizing the ZZγ vertices are independent because of different particles in the propagators.

	$e^+e^- \to$ ZZ	[?] [?] [?]
DELPHI:	$-2.7 < f_4^Z < +2.7$	$-1.6 < f_4^\gamma < +1.6$
	$-7.1 < f_5^Z < +5.7$	$-3.9 < f_5^\gamma < +3.9$
L3:	$-1.9 < f_4^Z < +1.9$	$-1.1 < f_4^\gamma < +1.1$
	$-4.9 < f_5^Z < +4.7$	$-3.0 < f_5^\gamma < +2.9$
OPAL:	$-2.0 < \Re\{f_4^Z\} < +2.0$	$-1.2 < \Re\{f_4^\gamma\} < +1.2$
	$-5.1 < \Re\{f_5^Z\} < +5.1$	$-3.2 < \Re\{f_5^\gamma\} < +3.0$
	$-2.0 < \Im\{f_4^Z\} < +1.9$	$-1.2 < \Im\{f_4^\gamma\} < +1.2$
	$-5.2 < \Im\{f_5^Z\} < +5.4$	$-3.2 < \Im\{f_5^\gamma\} < +3.0$

	$e^+e^- \to q\bar{q}\gamma$, $\nu\bar{\nu}\gamma$ and $p\bar{p} \to Z\gamma + X$	[?]
DELPHI*:	$-0.34 < h_1^Z < 0.33$	$-0.21 < h_1^\gamma < 0.21$
	$-0.20 < h_2^Z < 0.33$	$-0.13 < h_2^\gamma < 0.13$
	$-0.41 < h_3^Z < 0.27$	$-0.01 < h_3^\gamma < 0.07$
	$-0.18 < h_4^Z < 0.24$	$-0.05 < h_4^\gamma < 0.00$
L3:	$-0.71 < h_1^Z < 0.29$	$-0.33 < h_1^\gamma < 0.23$
	$-1.22 < h_2^Z < 0.21$	$-0.56 < h_2^\gamma < 0.17$
	$-0.56 < h_3^Z < 0.63$	$-0.16 < h_3^\gamma < 0.43$
	$-0.93 < h_4^Z < 1.04$	$-0.18 < h_4^\gamma < 0.57$
DØ **:	$\lvert h_{30}^Z \rvert < 0.36$	$\lvert h_{30}^\gamma \rvert < 0.37$
	$\lvert h_{40}^Z \rvert < 0.05$	$\lvert h_{40}^\gamma \rvert < 0.05$

* $\Lambda = 1000$ GeV ** $\Lambda = 750$ GeV

Table 7. Summary of limits (95% CL) on anomalous Z-photon couplings. If not stated otherwise limits are derived for the real part of the coupling. L3 and OPAL limits are derived up to $\sqrt{s} = 189$ GeV, DELPHI up to 202 GeV.

$$-0.006 \text{ GeV}^{-2} < a_c/\Lambda^2 < 0.011 \text{ GeV}^{-2}$$

These results are in agreement with the zero value of anomalous coupling as predicted from SM. These value are in agreements with those measured in $WW\gamma$ and $\nu\nu\gamma$ final states [?].

5. Interpretation of the electroweak measurements in the SM

5.1. Z boson physics and fits in the SM framework

All measurements at cms energies around Z pole and above show a good consistency with the SM expectations. These observables, cross sections and asymmetries, are also calculated in SM framework using five input variables, which are the free parameters of a fit: the masses of the Z and Higgs bosons and the top quark, the QED and the strong coupling constants at the Z. It should be noticed that the calculation of these observables at the Z resonance demand the precise knowledge of the QED coupling constant α at the Z and the contribution from the five light quark flavours has a relative uncertainty of about 2% [?].

Top quark and Higgs boson masses enter into SM relations through weak radiative corrections [?, ?]. In fact, the observables at the Z resonance depend, via corrections to Z and W propagator, quadratically on the top quark mass and on the logarithm of the Higgs mass.

In addition, the experimental value of the top quark mass measured by the Tevatron experiments [?] can be used and the effective weak mixing angle $\sin^2\overline{\vartheta}_W$ and the W boson mass can be derived.

5.2. Test of the SM model

At this point a very powerfull test of the SM is provided by the comparison of direct and indirect mass measurements. The direct measurements of

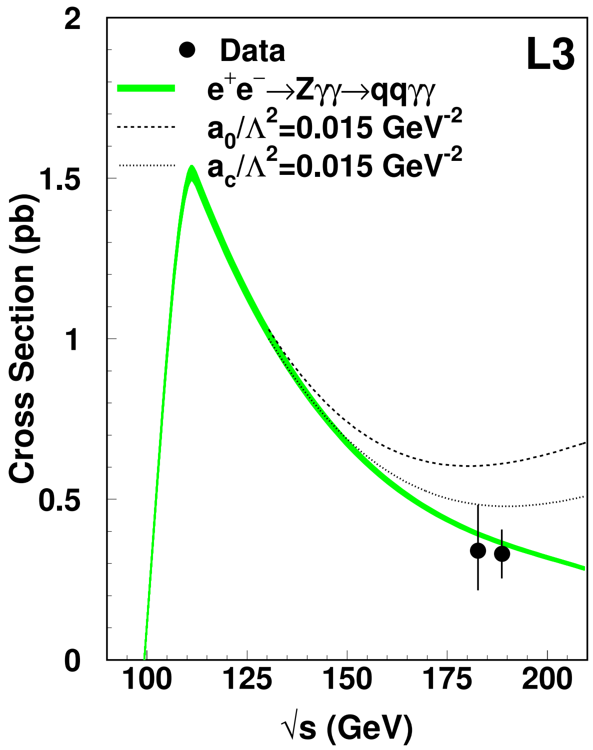

Figure 17. Evolution of $e^+e^- \rightarrow$ hadrons + $\gamma\gamma$ cross section.Dashed and dotted lines represent AQGC predictions.

W boson mass at LEP is [?]:

$$m_{\mathrm{W}} = 80.401 \pm 0.049 \text{ GeV} \tag{12}$$

and direct measurents of W boson a and top mass at Tevatron are: [?]:

$$m_{\mathrm{W}} = 80.448{\pm}0.062\,\text{GeV} \qquad m_{\mathrm{t}} = 174.3{\pm}5.1\,\text{GeV} \tag{13}$$

Comparing these values with those obtained from SM fit:

$$m_{\mathrm{W}} = 80.368{\pm}0.034\,\text{GeV} \qquad m_{\mathrm{t}} = 167.3{\pm}8.8\,\text{GeV} \tag{14}$$

a perfect agreement is found.

This is an important confirmation of the existence of weak radiative corrections. Their magnitude is as predicted by the SM showing that the theory is correct beyond the tree level. Then, if the theory is able to predict correctly the top mass, it should be able to predict as well the mass of the Higgs boson.

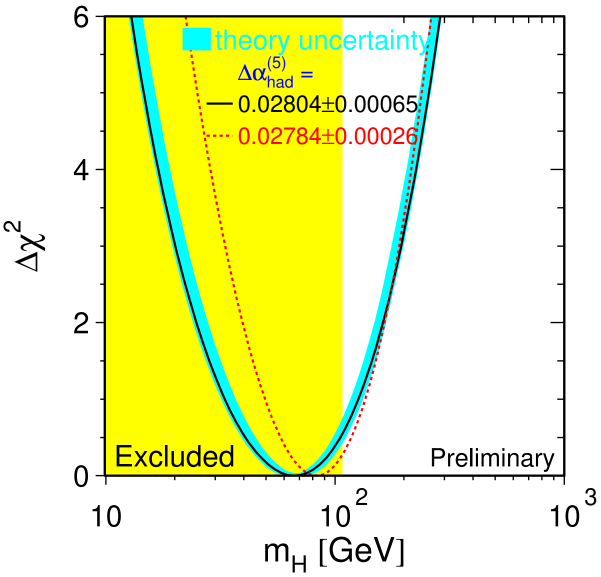

Figure 18. The line is the result of the fit to all electroweak precision data. The band represents an estimate of the theoretical error due to missing higher order corrections.The dashed line represents the result of the fit using the determination of $\Delta\alpha^{(5)}_{\mathrm{had}}$ of reference [?]. The band shows the 95% CL exclusion limit on Higgs boson mass from direct search [?].

5.3. The mass of the Higgs boson

To predict the mass of Higgs boson a very illustrative way is to study the dependence of the χ^2 of the SM fit to all electroweak precision data on m_{H} is shown in Fig. **??**. From this curve an upper limit on the Higgs mass is derived:

$$m_{\mathrm{H}} < 188 \text{ GeV} \qquad 95\% \text{ CL}\,. \tag{15}$$

This limit has to be compared with that one obtained from direct search for Higgs boson at LEP. No evidence for Higgs signal has been found in the experiments, so far, up to $\sqrt{s} \leq 202$ GeV which translates into a lower limit on the mass of [**?**]:

$$m_{\mathrm{H}} > 107.7 \text{ GeV} \qquad 95\% \text{ CL}\,. \tag{16}$$

The search for the Higgs boson together with the limit obtained from electroweak measurements are now severely constraining the allowed mass range for the last unknown member of this family.

6. Summary and outlook

The Z physics has been in detail studied during a decade of precision measurements at LEP and SLD. During the first phase of LEP running the Z parameters have been determined with a precision exceeding the most optimistic expectations. The univerisality of the lepton couplings to the Z boson has been proved.

All these experimental results confirm the SM with high precision.

In the second phase of LEP scientific program, the accelerator is operating at cms energies above Z pole. The contributions of γZ interference and Z boson exchange to fermion-pair production has been studied. At these energies the production of two bosons in the final state is possible and consequently to study the triple-gauge-coupling in the neutral sector, as ZZZ, ZZγ and Z$\gamma\gamma$. All these results can be nicely accomodate in the SM.

Moreover, this model reveals its power also giving an insight into the last unknown article: the Higgs boson. The indirect determination of the Higgs boson mass from electroweak precision data constitues a compelling evidence that it is light, with $m_{\mathrm{H}} < 188$ GeV. Combining this results with the Higgs boson direct search, $m_{\mathrm{H}} > 108$ GeV, the window mass for the last unknown member of the SM family is significantly constrained. This extraordinary result has been possible thanks to an extraordinary accelerator, extraordinary experiments and extraordinary model.

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