Extraction of α_s and Constraint on the Higgs Mass from Electroweak Fits at the Z Resonance

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Abstract

The determination of the Z lineshape parameters at LEP1 are presented and the value of $\alpha_s(M_Z^2)$ is derived from these measurements. The constraint on the Higgs mass obtained from a global fit to LEP1 and SLC data is also given.

1 Introduction

From 1990 to October 1995 the LEP e^+e^- storage ring was operated at center-of-mass energies close to the Z mass (called LEP1 program). LEP1 data have been collected and analysed by the 4 LEP experiments ALEPH[1], DELPHI[2], L3[3] and OPAL[4], the electroweak results and their combination are given in Ref.[5] and are still preliminary. Since 1992 the SLD detector is taking data on the SLC e^+e^- storage ring operating at center-of-mass energies also close to M_Z with polarised electron beam. The preliminary results from SLD include 1992 to 1997 data [6].
The cross sections and the asymmetries of the reactions $e^+e^- \to f\bar{f}(\gamma)$ measured at LEP and SLC are sensitive, through radiative corrections, to the

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following Standard Model parameters: the strong coupling constant α_s, the Higgs mass M_H and the top mass M_t. The value of α_s is mainly determined by the LEP total cross section measurements, while the asymmetries measured at LEP and SLC are most sensitive to M_H. We will concentrate on the determination of α_s and therefore on the determination of the Z lineshape parameters at LEP.

2 The Z lineshape and the fitting procedure

At LEP, an integrated luminosity of 110 pb^{-1} per experiment has been accumulated at the Z peak and about 40 pb^{-1} off peak, mostly at $M_Z \pm 1.8$ GeV. About 4 million hadronic and 0.5 million leptonic Z decays have been collected by each of the four LEP experiments. This large sample allows a precise determination of the Z boson properties: the Z mass M_Z, the Z width Γ_Z, the total hadronic cross section at the pole σ^0_{had} and the ratio of hadronic to leptonic pole cross sections $R_\ell = \sigma^0_{had}/\sigma^0_l \equiv \Gamma_{had}/\Gamma_l$.
These parameters have the advantage of being almost uncorrelated:

- M_Z is determined by the position of the peak and therefore depends on the absolute energy scale. Its uncertainty is dominated by the uncertainty on the LEP energy which is about 1.5 MeV[5].

- Γ_Z is determined by the width of the Z resonance. and therefore by peak and off peak relative cross section measurements. The uncertainty on Γ_Z comes mainly from uncorrelated errors on the off peak energy measurement ($\sim$1.5 MeV[5]) and from off peak statistics.

- σ^0_{had} is determined by the height of the resonance and is derived from the measurement of the hadronic cross section. The statistical and systematic uncertainties of the selections are typically of the order of 0.5×10^{-3} and 0.8×10^{-3} respectively, for each experiment[5]. The error on σ^0_{had} is dominated by the theoretical uncertainty on the luminosity which is 1.1×10^{-3}. Note that a recent study on the theoretical precision of the LEP luminosity[7] will lead to a reduction of this error to 0.6×10^{-3}.

- R_ℓ is determined by the measurement of the leptonic and hadronic cross sections. Since R_ℓ is a ratio, the uncertainty arising from the luminosity cancels and thus the uncertainty on R_ℓ comes only from the statistical and systematic errors in the $e^+e^- \to f\bar{f}$ event selections which will be discussed in Section 3.

The lowest order diagrams involved in the process $e^+e^- \to f\bar{f}$ are shown in Figure 1. The cross section is the sum of the Z exchange, the γ exchange

Figure 1: *Lowest order diagrams contributing to the* $e^+e^- \to f\bar{f}$ *cross section.*

and their interference

$$\sigma = \sigma_Z + \sigma_\gamma + \sigma_{int} \tag{1}$$

The cross section due to the Z exchange is parametrised with a Breit-Wigner in a model independent way using M_Z, Γ_Z, and the Z partial widths Γ_f

$$\sigma_Z = \sigma_f^0 \frac{s\Gamma_Z^2}{(s - M_Z^2)^2 + (s\Gamma_Z^2/M_Z^2)^2} \quad \text{with} \quad \sigma_f^0 = \frac{12\pi\Gamma_e\Gamma_f}{M_Z^2\Gamma_Z^2} \tag{2}$$

The photon contribution is taken from QED

$$\sigma_\gamma = \frac{4\pi\alpha^2}{3s} Q_e^2 Q_f^2 N_f^C \tag{3}$$

where N_F^C is the number of colours for quarks and 1 for leptons. The interference term contains combinations of the couplings of the fermions to the Z and their charge, which cannot be expressed in terms of the Z parameters used in equation 2 and are included in the J_f parameter

$$\sigma_{int} = \frac{4\pi\alpha^2}{3s} J_f \frac{s - M_Z^2}{(s - M_Z^2)^2 + (s\Gamma_Z^2/M_Z^2)^2} \tag{4}$$

Since the interference term is expected to be small it is usually set to the Standard Model value introducing a small model dependence in the fit.

Parameter	LEP average
M_Z	91.1867 ± 0.0020
Γ_Z	2.4948 ± 0.0025
σ^0_{had}	41.486 ± 0.053
R_ℓ	20.775 ± 0.027

Table 1: *Average line shape parameters from the results of the four LEP experiments.*

The effect of initial state radiation is taken into account in the fitting procedure through its convolution with the Born cross section. The fitted Z lineshape parameters are given in Table 1. These are the physical parameters, i.e they include all electroweak and strong radiative corrections and QED final state corrections:

$$\Gamma_f = \frac{G_F M_Z^3}{6\pi\sqrt{2}}\left(g_{A,f}^2 + g_{V,f}^2\right)\left(1+\delta_{QED}\right)\left(1+\delta_{QCD}\right) \tag{5}$$

The QCD correction δ_{QCD} is zero for leptons and is to a first approximation proportional to $(1+\alpha_s/\pi)$ for hadrons. The coupling constants $g_{A,f}$ and $g_{V,f}$ absorb the electroweak corrections through $\Delta\rho$ and $\sin^2\theta_{eff}^{lept}$:

$$g_{A,f} = \sqrt{1+\Delta\rho}\times I_3 \qquad g_{V,f} = \sqrt{1+\Delta\rho}\times (I_3 - 2Q_f \sin^2\theta_{eff}^{lept}) \tag{6}$$

The dependence of $\Delta\rho$ and of $\sin^2\theta_{eff}^{lept}$ on M_t is quadratic, while the dependence on the Higgs mass is only logarithmic giving less sensitivity to M_H. These radiative corrections are detailed in [8].
The measured values of the Z parameters are confronted with the Standard Model prediction in order to extract the radiative corrections and therefore to determine α_s, M_H and M_t. This fit is performed using the latest version of the programs ZFITTER and TOPAZ0 [9] which include new calculations of radiative corrections:

- non factorisable QCD/EW corrections [10] resulting in an increase of the fitted value of α_s of $+0.001$ with respect to old versions.
- two loop irreducible EW corrections [11] $\mathcal{O}(\alpha^2 M_t^2/M_W^2)$ leading to a decrease in the Higgs mass of about 30 GeV/c^2.

- four loop QCD corrections in the β function [12].

Results will be given in the next Sections.

3 Extraction of α_s

The most sensitive parameters to α_s are Γ_Z, σ^0_{had} and R_ℓ. They all depend on α_s through Γ_{had}. Their dependence with α_s is given in a first approximation by:

$$R_\ell = \frac{\Gamma_{had}}{\Gamma_l} \propto \left(1 + \frac{\alpha_s}{\pi}\right) \quad (7)$$

$$\Gamma_Z = \Gamma_{had} + \Gamma_e + \Gamma_\mu + \Gamma_\tau + \Gamma_{inv} \propto \left(1 + 0.7\frac{\alpha_s}{\pi}\right) \quad (8)$$

$$\sigma^0_{had} \propto \frac{\Gamma_e \Gamma_{had}}{\Gamma_Z^2} \propto \left(1 - 0.4\frac{\alpha_s}{\pi}\right) \quad (9)$$

Table 2 gives the relative experimental precision on these parameters and the derived uncertainty on α_s when determined using only the corresponding parameter. R_ℓ and Γ_Z both allow to determine α_s with the same experimental precision[1] but Γ_Z varies rapidly with M_H introducing an additional uncertainty if no constraint on M_H is used whereas the M_H dependence of R_ℓ almost cancels in the ratio of the hadronic to leptonic widths. Therefore R_ℓ is the most sensitive to α_s and allows to determine α_s without any assumption on the Higgs mass.

	$\Delta x/x$	$\Delta\alpha_s$
R_ℓ	$1.3\ 10^{-3}$	0.004
Γ_Z	$1.0\ 10^{-3}$	0.004
σ^0_{had}	$1.3\ 10^{-3}$	0.010

Table 2: *Relative experimental precision on the parameters used in α_s determination and induced uncertainty on α_s.*

[1]The error on σ^0_{had} should decrease from 1.3×10^{-3} to about 0.9×10^{-3} with the decrease of the theoretical error on the luminosity[7] but σ^0_{had} will still be less powerful than R_ℓ to determine α_s.

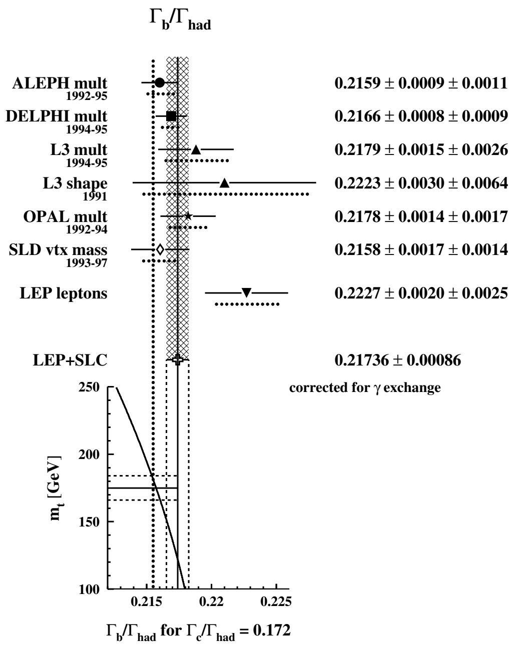

Figure 2: *Experimental determination of* $\mathrm{R_b^0}$ *at LEP and SLC. Also shown is the Standard Model expectation as a function of* $\mathrm{M_t}$ *and the direct top mass measurement* $\mathrm{M_t} = (174.1 \pm 5.4)$ *GeV/c^2[13].*

One should note that R_ℓ, Γ_Z and σ^0_had all depend on Γ_b through Γ_had and that $\mathrm{R_b^0} = \Gamma_\mathrm{b}/\Gamma_\mathrm{had}$ is fixed to its Standard Model value in order to extract α_s. However, since $\mathrm{R_b^0}$ is very sensitive to new physics through the $\mathrm{Zb\bar{b}}$ vertex corrections its value may deviate from Standard Model expectation. The experimental determination of $\mathrm{R_b^0}$ is shown in Figure 2 and is in agreement within 1.8σ with the SM prediction for the direct top mass measurement $\mathrm{M_t} = (174.1 \pm 5.4)$ GeV/c^2[13]. This value of $\mathrm{M_t}$ is used in the following.

The measurement of R_ℓ

As already discussed in Section 2, the uncertainty on R_ℓ is dominated by the dilepton statistical and systematic experimental errors. The preliminary measurements of the 4 LEP experiments [5] presented in Jerusalem 97 are shown in Figure 3. The statistical uncertainty is $\Delta\mathrm{R}_\ell/\mathrm{R}_\ell(\mathrm{stat}) \simeq (0.05(\mathrm{q\bar{q}}) \oplus$

$0.15(l^+l^-))\%$ for each LEP experiment. The systematic uncertainty from the hadronic channel is of the order of 0.08% and an effort is being made to reduce the systematic error from the leptonic channel.

A new measurement of R_ℓ using ALEPH data with a global dilepton selec-

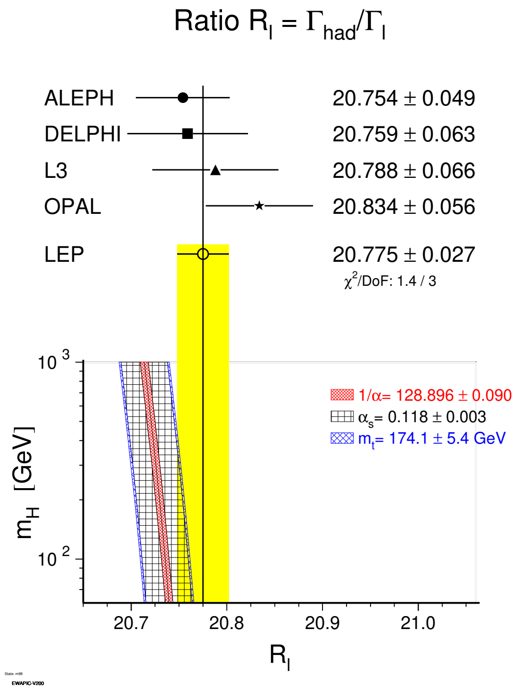

Figure 3: *Determination of* R_ℓ *at LEP. The Standard Model prediction as a function of* M_H *is also shown. The width of the Standard Model band correspond to the uncertainties on* α_s*,* M_t *and* $\alpha(M_Z^2)$*. The total width of the band is the linear sum of these effects.*

tion allows to reduce the systematic uncertainty from the leptonic channel to 0.08%. The dilepton selection has to be inclusive in order to be compared to the theoretical prediction. Therefore this selection includes also four fermion final state events of the type $\ell^+\ell^-V$ where ℓ is a lepton and V is a low invariant mass pair of fermions.

First, dileptons are selected with an efficiency of 99.2% inside the detector acceptance and background from $\gamma\gamma$, $q\bar{q}$ and cosmic events is reduced to the level of 0.2%. All the systematic uncertainties are at the level of few 10^{-4}. Then the lepton flavour separation is performed inside the dilepton sample so that the systematic uncertainties are anti-correlated between 2 lepton species and that no additional uncertainty is introduced on R_ℓ. This separation is needed in order to identify $e^+e^- \to e^+e^-$ events for which the t-channel contribution has to be subtracted. This subtraction is performed using theoretical calculation described in [14]. The theoretical error assigned to the subtraction is 0.08% of the $e^+e^- \to e^+e^-$ s-channel cross section[15]. The value of R_ℓ obtained with this new selection is

$$R_\ell = 20.732 \pm 0.038 \qquad \text{(ALEPH)} \tag{10}$$

The relative error on R_ℓ is reduced from 2.4×10^{-3} (1997 value) to 1.9×10^{-3} (this measurement).

Determination of α_s with R_ℓ

The dependence of R_ℓ on α_s is parametrised with the latest version of ZFITTER[9]:

$$R_\ell = 19.934\left(1 + 1.045\left(\frac{\alpha_s}{\pi}\right) + 0.94\left(\frac{\alpha_s}{\pi}\right)^2 - 15\left(\frac{\alpha_s}{\pi}\right)^3\right) \tag{11}$$

In this parametrisation $M_H = 300$ GeV/c^2 and $M_t = 174.1$ GeV/c^2 are used. The small dependence with the Higgs and the top masses is also parametrised with ZFITTER

$$R_\ell \propto \left(1 - 2.2 \times 10^{-4} \ln\left(\frac{M_H}{M_Z}\right)^2\right) \times \left(1 - 4.1 \times 10^{-4}\left(\frac{M_t}{M_Z}\right)^2\right) \tag{12}$$

The values of R_ℓ obtained with this parametrisation agree with ZFITTER prediction at the level of few 10^{-5} for any value of α_s in [0.100,0.130], M_t in [150,200] GeV/c^2 and M_H in [60,1000] GeV/c^2. Figure 4 shows the new ALEPH determination of R_ℓ and the Standard Model expectation as a function of α_s. The variation arising from M_H and M_t are also shown. The value obtained for α_s is

$$\alpha_s(M_Z^2) = 0.119 \pm 0.006_{\text{exp}} \pm 0.002_{\text{QCD}} \pm 0.002_{M_H} \;\; \text{(ALEPH)} \tag{13}$$

where the first error comes from the experimental uncertainty on R_ℓ, the second error covers missing higher-order corrections and uncertainties in the interplay of electroweak and QCD corrections[16] and the last error is obtained by varying the Higgs mass from 60 to 1000 GeV/c^2.

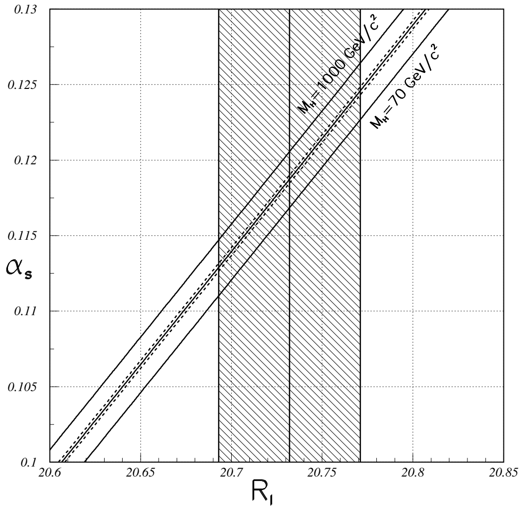

Figure 4: *ALEPH determination of* R_ℓ *(hatched band) and Standard Model expectation as a function of* α_s*. The full lines give the SM prediction for* $M_t = 174.1$ *GeV/c*^{2} *and* M_H *=70, 300, and 1000 GeV/c*^{2}*. The doted lines correspond to a variation of* M_t *of* ± 5 *GeV/c*^{2} *for* M_H *fixed to 300 GeV/c*^{2}*.*

The preliminary LEP combined value or R_ℓ (Jerusalem 97, see Ref.[5]) is shown in Figure 3 and leads to

$$\alpha_s(M_Z^2) = 0.125 \pm 0.004_{\rm exp} \pm 0.002_{\rm QCD} \pm 0.002_{M_H} \tag{14}$$

In an overall fit using all the information from LEP1 and SLC data (cross sections and asymmetries) the value of α_s and of M_H are simultaneously constrained (see Section 4), the fitted value of α_s is

$$\alpha_s(M_Z^2) = 0.120 \pm 0.003_{\rm exp} \pm 0.002_{\rm QCD} \tag{15}$$

The experimental error is reduced from 0.004 (in equation 14) to 0.003 because Γ_Z and $\sigma^0_{\rm had}$ are used in this last fit, and the 0.002 error from the Higgs mass disappears since M_H is also constrained. This value of α_s is lower than in the fit to R_ℓ alone (equation 14) because Γ_Z prefers lower values of α_s and the low fitted value of M_H (66 GeV/c^2) brings α_s down by $\sim$0.002 (in the fit to R_ℓ the value $M_H = 300$ GeV/c^2 was used). This value is in good agreement with the world average $\alpha_s(M_Z^2) = 0.118 \pm 0.003$[17] and of comparable precision.

4 Constraint on the SM Higgs mass

The determination of $\sin^2\theta_{eff}^{lept}$

At the Z resonance, the most sensitive parameter to the Higgs mass is $\sin^2\theta_{eff}^{lept}$ which is determined through the measurement of the asymmetries

- the lepton, b and c quarks Forward-Backward asymmetries $A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$ determined at LEP1 from $e^+e^- \to f\bar{f}$ angular distributions

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \cos^2\theta + \frac{8}{3}A_{FB}\cos\theta \tag{16}$$

- The τ polarisation (LEP1)

$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{1+\cos^2\theta + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta} \tag{17}$$

- the Left-Right asymmetries measured at SLC with polarised electron beam

$$A_{LR} = \mathcal{A}_e \tag{18}$$

where $\mathcal{A}_f = 2(g_{V,f}/g_{A,f})/(1+(g_{V,f}/g_{A,f})^2)$. All these quantities are expressed in terms of the effective mixing angles of leptons, $\sin^2\theta_{eff}^{lept}$. The derived values of $\sin^2\theta_{eff}^{lept}$ from the different asymmetry measurements [5] are compared in Figure 5. SLD and LEP average differ by 2σ and SLD data prefer lower values of the Higgs mass. Since all LEP data have been analysed new measurement can only come from SLC with increased statistics.

The global fit

In the global fit the electroweak measurements are compared to Standard Model predictions in order to determine simultaneously the values of $\alpha_s(M_Z^2)$, M_t and M_H. The parameters $G_F = (1.16639 \pm 0.00002) \times 10^{-5}$ GeV^{-2} from muon decay and $\alpha(M_Z^2)^{-1} = 128.896 \pm 0.090$ from [18] are also used as input in the fit. This global fit is performed with three data sets, results are given in Table 3:

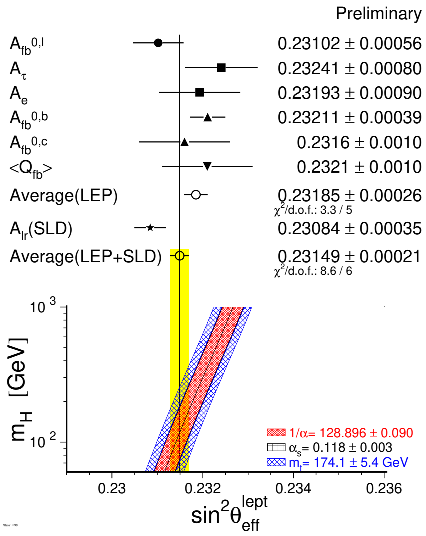

Figure 5: *Determinations of* $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ *from the asymmetries. The prediction from the Standard Model as a function of* $\mathrm{M_H}$ *is also shown. The width of the Standard Model band is due to the uncertainties in* $\alpha(\mathrm{M_Z^2})$, $\alpha_s(\mathrm{M_Z^2})$ *and* $\mathrm{M_t}$.

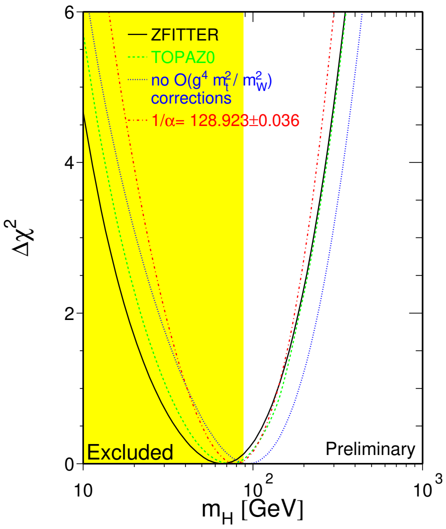

Figure 6: $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ *vs.* $\mathrm{M_H}$ *curve. The line is the result of the fit using all data (last column of Table 3). The vertical band shows the 95% CL exclusion limit on* $\mathrm{M_H}$ *from direct searches [21]*
.

1. A first fit to LEP data alone including the measurement of the W mass at LEP 2 is made (first column of Table 3). This fit shows that LEP data prefer a light top and a light Higgs.

2. Then LEP1 and SLD data and the measurement of $\sin^2\theta_{\mathrm{W}}$ from νN experiments are used to determine top quark and W masses indirectly (second column of Table 3). The good agreement with the direct measurements $\mathrm{M_t} = 174.1 \pm 5.4$ GeV/c^2[13] and $\mathrm{M_W} = 80.430 \pm 0.080$ GeV/c^2 [19] provides a test of the Standard Model.

3. All electroweak measurements including the direct $\mathrm{M_t}$ and $\mathrm{M_W}$ measurement are used to obtain the best constraint on $\mathrm{M_H}$ (last column of Table 3). Figure 6 shows the result of this fit using the latest version of ZFITTER and TOPAZ0. Also shown is the curve obtained when

	LEP including LEP2 M_W	all data except M_t and M_W	all data
M_t [GeV]	157^{+12}_{-10}	161^{+9}_{-8}	171.1 ± 5.1
M_H [GeV]	56^{+101}_{-31}	33^{+45}_{-17}	66^{+74}_{-39}
$\mathrm{Log}(M_H/\mathrm{GeV})$	$1.75^{+0.45}_{-0.35}$	$1.53^{+0.37}_{-0.29}$	$1.82^{+0.33}_{-0.40}$
$\alpha_s(M_Z^2)$	0.122 ± 0.003	0.121 ± 0.003	0.120 ± 0.003
χ^2/d.o.f.	6/9	14/12	17/15
$\sin^2\theta_W^{\mathrm{eff}}$	0.23183 ± 0.00025	0.23145 ± 0.00021	0.23146 ± 0.00022
$\sin^2\theta_W$	0.2245 ± 0.0008	0.2235 ± 0.0008	0.2230 ± 0.0005
M_W [GeV]	80.302 ± 0.040	80.351 ± 0.040	80.380 ± 0.027

Table 3: *Results of the electroweak fits. See text for details.*

new higher-order corrections are neglected ('no $\mathcal{O}(g^4 M_t^2/M_W^2)$' curve). These corrections lead to a decrease of the Higgs mass of ~ 30 GeV/c^2. The upper limit on M_H is 215 GeV/c^2 at 95% CL. The uncertainty on $\alpha(M_Z^2)$ causes an error of 0.2 on $\mathrm{Log}(M_H)$. The fit is also performed with the new evaluation of $\alpha(M_Z^2)$[20]. With this value the fitted error on $\mathrm{Log}(M_H)$ is reduced by 30% (from 0.33 to 0.25).

Since M_H is mainly constrained by the measurement of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$, new data from SLC will improve this constraint. Moreover, radiative corrections are shared between the top quark and the Higgs, therefore the reduction of the error on the direct top mass measurement will improve the constraint on the Higgs mass. The W mass is also sensitive to the Higgs mass and its measurement with an error of 30 MeV at LEP2 will also improve the constraint on M_H.

5 Conclusion

The large sample of data accumulated at LEP1 allows the determination of α_s through radiative corrections, $\alpha_s = 0.120 \pm 0.003_{\mathrm{exp}} \pm 0.002_{\mathrm{QCD}}$ with a precision comparable to the world average (in which LEP1 data have not

been included). Since all LEP1 data have been analysed, this determination may only slightly improve through the reduced error on $\sigma^0_{\rm had}$[7].
The global fit gives for the Higgs mass

$$\mathrm{M_H} = 66^{+74}_{-39} \ \ \mathrm{GeV/c^2} \tag{19}$$

There is still room for improvement in this constraint through better top and W mass direct measurements, new data from SLC and the reduction of the error on $\alpha(\mathrm{M_Z^2})$.
A low value of the Higgs mass is preferred by the Z resonance data: it is still possible to find the Higgs at LEP2 !

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