Extraction of $\alpha_s$ and constraint on the Higgs mass from Electroweak fits at the Z resonance

Edwige TOURNEFIER
Laboratoire de l’Accélérateur Linéaire
IN2P3-CNRS et Université de Paris-Sud,
BP34, F-91898 Orsay Cedex

Abstract

The determination of the Z lineshape parameters at LEP1 is 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.

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1e-mail: Edwige.Tournefier@cern.ch
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, DELPHI, L3 and OPAL, the electroweak results and their combination are given in Ref. 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.

The cross sections and the asymmetries of the reactions $e^+e^- \rightarrow \bar{f}f(\gamma)$ measured at LEP and SLC are sensitive, through radiative corrections, to the following Standard Model parameters: the strong coupling constant $\alpha_s$, the Higgs mass $M_H$ and the top mass $M_t$. The value of $\alpha_s$ 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 $\alpha_s$ 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 $\Gamma_Z$, the total hadronic cross section at the pole $\sigma^0_{\text{had}}$ and the ratio of hadronic to leptonic pole cross sections $R_\ell = \sigma^0_{\text{had}}/\sigma^0_\ell \equiv \Gamma_{\text{had}}/\Gamma_\ell$.

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.

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

- $\sigma^0_{\text{had}}$ 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 $0.5 \times 10^{-3}$ and $0.8 \times 10^{-3}$ respectively, for each experiment. The error on $\sigma^0_{\text{had}}$ is dominated by the theoretical uncertainty on the luminosity which is $1.1 \times 10^{-3}$. Note that a recent study on the theoretical precision of the LEP luminosity will lead to a reduction of this error to $0.6 \times 10^{-3}$.

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

![Diagram](image)

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

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

$$\sigma = \sigma_Z + \sigma_\gamma + \sigma_{\text{int}}$$  \hspace{1cm} (1)

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

$$\sigma_Z = \sigma^0_f \frac{s\Gamma^2_Z}{(s-M^2_Z)^2+(s\Gamma^2_Z/M^2_Z)^2} \quad \text{with} \quad \sigma^0_f = \frac{12\pi\Gamma_e\Gamma_f}{M_Z^2\Gamma^2_Z}$$  \hspace{1cm} (2)
| Parameter | LEP average |
|-----------|-------------|
| $M_Z$     | 91.1867 ± 0.0020 |
| $\Gamma_Z$ | 2.4948 ± 0.0025 |
| $\sigma^0_{\rm had}$ | 41.486 ± 0.053 |
| $R_f$     | 20.775 ± 0.027 |

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

The photon contribution is taken from QED

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

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

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

The QCD correction $\delta_{\text{QCD}}$ 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 $\sin^2\theta_{\text{eff}}^{\text{lept}}$:

$$g_{A,f} = \sqrt{1 + \Delta\rho} \times I_3 \quad g_{V,f} = \sqrt{1 + \Delta\rho} \times (I_3 - 2Q_f \sin^2\theta_{\text{eff}}^{\text{lept}})$$  \hfill (6)
The dependence of $\Delta \rho$ and of $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ 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 $\alpha_s$, $M_H$ 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 $\alpha_s$ of +0.001 with respect to old versions.
- two loop irreducible EW corrections $\mathcal{O}(\alpha^2 M_t^2/M_W^2)$ leading to a decrease in the Higgs mass of about 30 GeV/c$^2$.
- four loop QCD corrections in the $\beta$ function [12].

Results will be given in the next Sections.

3 Extraction of $\alpha_s$

The most sensitive parameters to $\alpha_s$ are $\Gamma_Z$, $\sigma^0_{\text{had}}$ and $R_\ell$. They all depend on $\alpha_s$ through $\Gamma_{\text{had}}$. Their dependence with $\alpha_s$ is given in a first approximation by:

$$R_\ell = \frac{\Gamma_{\text{had}}}{\Gamma_1} \propto \left(1 + \frac{\alpha_s}{\pi}\right)$$

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

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

Table 2 gives the relative experimental precision on these parameters and the derived uncertainty on $\alpha_s$ when determined using only the corresponding parameter. $R_\ell$ and $\Gamma_Z$ both allow to determine $\alpha_s$ with the same experimental precision but $\Gamma_Z$ varies rapidly with $M_H$ introducing an additional

$^2$The error on $\sigma^0_{\text{had}}$ should decrease from $1.3 \times 10^{-3}$ to about $0.9 \times 10^{-3}$ with the decrease of the theoretical error on the luminosity but $\sigma^0_{\text{had}}$ will still be less powerful than $R_\ell$ to determine $\alpha_s$. 

4
Table 2: Relative experimental precision on the parameters used in $\alpha_s$ determination and induced uncertainty on $\alpha_s$.

| Parameter       | $\Delta x/x$ | $\Delta \alpha_s$ |
|-----------------|--------------|-------------------|
| $R_\ell$        | $1.3 \times 10^{-3}$ | 0.004             |
| $\Gamma_Z$      | $1.0 \times 10^{-3}$ | 0.004             |
| $\sigma^0_{\text{had}}$ | $1.3 \times 10^{-3}$ | 0.010             |

uncertainty if no constraint on $M_H$ is used whereas the $M_H$ dependence of $R_\ell$ almost cancels in the ratio of the hadronic to leptonic widths. Therefore $R_\ell$ is the most sensitive to $\alpha_s$ and allows to determine $\alpha_s$ without any assumption on the Higgs mass.

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

The measurement of $R_\ell$

As already discussed in Section 4, the uncertainty on $R_\ell$ 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 $\Delta R_\ell/R_\ell(\text{stat}) \simeq (0.05(\text{qq}) \oplus 0.15(1^{+1-})))\%$ 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 $R_\ell$ using ALEPH data with a global dilepton selection 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 $\ell$ 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.
Figure 2: Experimental determination of $R_0$ at LEP and SLC. Also shown is the Standard Model expectation as a function of $M_t$ and the direct top mass measurement $M_t = (174.1 \pm 5.4) \text{ GeV}/c^2 [13]$. 

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 $R_{\ell}$. This separation is needed in order to identify $e^+e^- \rightarrow e^+e^-$ 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 $e^+e^- \rightarrow e^+e^-$ s-channel cross section [15]. The value of $R_{\ell}$ obtained with this new selection is

$$R_{\ell} = 20.732 \pm 0.038 \quad (\text{ALEPH})$$

(10)

The relative error on $R_{\ell}$ is reduced from $2.4 \times 10^{-3}$ (1997 value) to $1.9 \times 10^{-3}$ (this measurement).
Figure 3: Determination of $R_\ell$ at LEP. The Standard Model prediction as a function of $M_H$ is also shown. The width of the Standard Model band corresponds to the uncertainties on $\alpha_s, M_t$ and $\alpha(M_Z^2)$. The total width of the band is the linear sum of these effects.

**Determination of $\alpha_s$ with $R_\ell$**

The dependence of $R_\ell$ on $\alpha_s$ is parametrised with the latest version of ZFITTER $^9$:

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

(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

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

(12)

The values of $R_\ell$ obtained with this parametrisation agree with ZFITTER prediction at the level of few $10^{-5}$ for any value of $\alpha_s$ 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 \(R_\ell\) and the Standard Model expectation as a function of \(\alpha_s\). The variations arising from \(M_H\) and \(M_t\) are also shown. The value obtained for \(\alpha_s\) is

\[
\alpha_s(M_Z^2) = 0.119 \pm 0.006_{\text{exp}} \pm 0.002_{\text{QCD}} \pm 0.002_{M_H} \quad \text{(ALEPH)}
\]  

where the first error comes from the experimental uncertainty on \(R_\ell\), 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\(^2\).

The preliminary LEP combined value or \(R_\ell\) (Jerusalem 97, see Ref.\(^5\)) is shown in Figure 3 and leads to

\[
\alpha_s(M_Z^2) = 0.125 \pm 0.004_{\text{exp}} \pm 0.002_{\text{QCD}} \pm 0.002_{M_H}
\]  

(14)
In an overall fit using all the information from LEP1 and SLC data (cross sections and asymmetries) the value of $\alpha_s$ and of $M_H$ are simultaneously constrained (see Section 4), the fitted value of $\alpha_s$ is

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

(15)

The experimental error is reduced from 0.004 (in equation (14)) to 0.003 because $\Gamma_Z$ and $\sigma^{0}_{\text{had}}$ 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 $\alpha_s$ is lower than in the fit to $R_\ell$ alone (equation (14)) because $\Gamma_Z$ prefers lower values of $\alpha_s$ and the low fitted value of $M_H$ (66 GeV/c$^2$) brings $\alpha_s$ down by $\sim 0.002$ (in the fit to $R_\ell$ the value $M_H = 300$ GeV/c$^2$ was used). This value is in good agreement with the world average $\alpha_s(M_Z^2) = 0.118 \pm 0.003$ and of comparable precision.

4 Constraint on the SM Higgs mass

The determination of $\sin^2 \theta^\text{lept}_{\text{eff}}$

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

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

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

(16)

- The $\tau$ polarisation (LEP1)

$$P_\tau(\cos\theta) = -\frac{A_\tau(1 + \cos^2\theta) + 2 A_e \cos\theta}{1 + \cos^2\theta + 2 A_e A_\tau \cos\theta}$$

(17)

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

$$A_{LR} = A_e$$

(18)

where $A_f = 2(g_{V,f}/g_{A,f})/(1 + (g_{V,f}/g_{A,f})^2)$. All these quantities are expressed in terms of the effective mixing angles of leptons, $\sin^2 \theta^\text{lept}_{\text{eff}}$. The derived values of $\sin^2 \theta^\text{lept}_{\text{eff}}$ from the different asymmetry measurements are compared
in Figure 5. SLD and LEP average differ by $2\sigma$ 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

![Figure 5](image_url)

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

![Figure 6](image_url)

**Figure 6:** $\Delta \chi^2 = \chi^2 - \chi_{\text{min}}^2$ vs. $M_H$ 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 $M_H$ from direct searches [21].

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:

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 $\sin^2 \theta_W$ from $\nu N$ experiments are used to determine top quark and W masses indirectly (second column of Table 3). The good agreement with the direct measurements $M_t = 174.1 \pm 5.4$ GeV/c$^2$\cite{13} and $M_W = 80.430 \pm 0.080$ GeV/c$^2$\cite{19} provides a test of the Standard Model.

3. All electroweak measurements including the direct $M_t$ and $M_W$ measurement are used to obtain the best constraint on $M_H$ (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 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 $\sim 30$ 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 Log($M_H$). The fit is also performed with the new evaluation of $\alpha(M_Z^2)$\cite{20}. With this value the fitted error on Log($M_H$) is reduced by 30% (from 0.33 to 0.25).

Since $M_H$ is mainly constrained by the measurement of $\sin^2 \theta_W^{\text{lept}}$, 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 $\alpha_s$ through radiative corrections, $\alpha_s = 0.120 \pm 0.003_{\text{exp}} \pm 0.002_{\text{QCD}}$ 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 $\sigma^0_{\text{had}}$ [7].

The global fit gives for the Higgs mass

$$M_H = 66^{+74}_{-39} \text{ GeV}/c^2 \quad (19)$$

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 $\alpha(M^2_Z)$.

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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**References**
[1] ALEPH Collaboration, D. Decamp et al., Z. Phys C48 (1990) 365;
ALEPH Collaboration, D. Decamp et al., Z. Phys C53 (1992) 1;
ALEPH Collaboration, D. Buskulic et al., Z. Phys C60 (1993) 71;
ALEPH Collaboration, D. Buskulic et al., Z. Phys C62 (1994) 539;
ALEPH Collaboration, Preliminary results on Z production Cross Section and Lepton Forward-Backward Asymmetries using the 1990-1995 Data, contributed paper to ICHEP96, Warsaw, July 1996, PA07-069; updated for EPS-HEP-97, Jerusalem.

[2] DELPHI Collaboration, P. Aarnio et al., Nucl.Phys. B367 (1991) 511;
DELPHI Collaboration, P. Abreu et al., Nucl.Phys. B417 (1994) 3;
DELPHI Collaboration, P. Abreu et al., Nucl.Phys. B418 (1994) 403;
DELPHI Collaboration, DELPHI Note 95-62 PHYS 497, contributed paper to EPS-HEP-95 Brussels, eps0404;
DELPHI Collaboration, DELPHI Note 97-130 CONF 109, contributed paper to EPS-HEP-97 Jerusalem EPS-463.

[3] L3 Collaboration, B. Adeva et al., Z. Phys. C51 (1991) 179;
L3 Collaboration, O. Adriani et al., Phys. Rep. 236 (1993) 1;
L3 Collaboration, M. Acciarri et al., Z. Phys. C62 (1994) 551;
L3 Collaboration, Preliminary L3 Results on Electroweak Parameters using 1990-96 Data, L3 Note 2065, March 1997, available via http://hpl3sn02.cern.ch/note/note-2065.ps.gz

[4] OPAL Collaboration, G. Alexander et al., Z. Phys. C52 (1991) 175;
OPAL Collaboration, P.D. Acton et al., Z. Phys. C58 (1993) 219;
OPAL Collaboration, R. Akers et al., Z. Phys. C61 (1994) 19;
OPAL Collaboration, OPAL physics Notes PN142(1994), PN166(1995), PN242(1996);
OPAL Collaboration, Measurements of Lepton Pair Asymmetries using the 1995 Data, contributed paper to ICHEP96, Warsaw, 25-31 July 1996 PA07-015;
OPAL Collaboration, A preliminary Update of the Z Lineshape and Lepton Asymmetry Measurements with the 1995 Data, OPAL Physics Note PN286, March 1997.

[5] The LEP Collaborations ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group and the SLD Heavy Flavour and Electroweak
Groups, *A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model*, Internal Note, LEPEWWG/98-01, May 1998.

[6] G. Crawford, *Precision Electroweak Tests Recent Results from SLD*, XXXIIIrd Rencontres de Moriond, Les Arcs, France, 14-21 March 1998.

[7] S. Jadach, M. Melles, B.F.L. Ward and S.A. Yost, *New Results on the Theoretical Precision of the LEP/SLC Luminosity*, UTHEP-98-0501, May 1998.

[8] Reports of the working group on precision calculations for the Z resonance, eds. D. Bardin, W. Hollik and G. Passarino, CERN Yellow Report 95-03, Geneva, March 1995.

[9] ZFITTER: D. Bardin et al., *Z. Phys. C44* (1989) 493; Comp. Phys. Comm. 59 (1990) 303; Nucl. Phys. B351 (1991) 1; Phys. Lett. B255 (1991) 290 and CERN-TH 6443/92 (May 1992); TOPAZ0: G. Montagna, O. Nicrosini, G. Passarino, F. Piccinnii and R. Pittau, Nucl. Phys. B401 (1993) 3; Comp. Phys. Comm 76 (1993) 328.

These computer codes have been recently updated with results from [8], [10], [11] and [12].

[10] A. Czarnecki and J. Kühn, Phys. Rev. Lett. 77 (1996) 3955; R. Harlander, T. Seidensticker and M. Steinhauser, [hep-ph/9712228](https://arxiv.org/abs/hep-ph/9712228).

[11] G. Degrassi, P. Gambino and A. Vicini Phys. Lett. B383 (1996) 219; G. Degrassi, P. Gambino and A. Sirlin Phys. Lett. B394 (1997) 188.

[12] S. Larin, T.v. Ritbergen and J. Vermaseren, Phys. Lett. B400 (1997) 379, B405 (1997) 327; K. Chetyrkin, B. Kniehl and M. Steinhauser, Phys. Rev. Lett. 79 (1997) 2184, [hep-ph/9708255](https://arxiv.org/abs/hep-ph/9708255).

[13] M. Jones, *Tevatron Top Mass Measurements*, XXXIIIrd Rencontres de Moriond, Les Arcs, France, 14-21 March 1998.

[14] W. Beenakker, F.A. Berends and S.C. van der Marck, *Large Angle Bhabha Scattering*, Nucl. Phys. B349 (1991) 223.
[15] W. Beenakker and G. Passarino, *Large Angle Bhabha Scattering at LEP1*, Phys. Lett. **B425** (1998) 199.

[16] T. Hebbeker, M. Martinez, G. Passarino and G. Quast, Phys Lett. **B331** (1994) 165;
    P.A. Raczka and Szymacha, Phys. Rev. **D54** (1996)3073;
    D.E. Soper and L.R. Surguladze, Phys. Rev **D54** (1996) 4566.

[17] R.M. Barnett *et al.*, Phys. Rev. **D54** (1996) 1.

[18] S. Eidelmann and F. Jegerlehner, Z. Phys **C67** (1995) 585.

[19] Y.K. Kim, talk presented at the Lepton Photon Symposium 1997, Hamburg, 28 July-1 Aug, 1997, to appear in the proceedings.

[20] M. Davier and A. Höcker, *Improved Determination of $\alpha(m_Z^2)$ and the Anomalous Magnetic Moment of the Muon*, LAL 97-85, hep-ph/9711308, Nov 1997.

[21] S. de Jong, talk presented at the XXXIIIrd Rencontres de Moriond, Les Arcs, France, 15-21 March 1998.