September 20, 1996 HUB-EP-96/50

Combined Precision Electroweak Results from LEP/SLC

Martin W. Grünewald

Humboldt-Universität zu Berlin
Institut für Physik
Invalidenstr. 110
D-10115 Berlin

Abstract

A combination of published and preliminary results of electroweak measurements from the four LEP collaborations and the SLD collaboration is presented. Averages are derived from the measurements of cross sections, forward-backward and polarisation asymmetries. These data are used to determine the parameters of the Standard Model.

Invited talk presented at the 28th International Conference on High Energy Physics, Warsaw, Poland, July 25-31, 1996

Combined Precision Electroweak Results from LEP/SLC

Martin W. Grünewald

Humboldt University Berlin, Invalidenstr. 110, D-10115 Berlin, e-mail: `Martin.Grunewald@cern.ch`

A combination of published and preliminary results of electroweak measurements from the four LEP collaborations and the SLD collaboration is presented. Averages are derived from the measurements of cross sections, forward-backward and polarisation asymmetries. These data are used to determine the parameters of the Standard Model.

1 Introduction

The four LEP experiments and the SLD collaboration study e^+e^- interactions at centre-of-mass energies, $\sqrt{s}$, around 91 GeV, corresponding to the mass of the Z boson. The measurements consist of total cross sections, leptonic forward-backward asymmetries, tau polarisation asymmetries, b and c quark decay widths and forward-backward asymmetries. Because of beam polarisation at SLC, SLD also measures the left-right polarisation asymmetry and the left-right forward-backward polarisation asymmetries for heavy quarks. In the following, the combination procedure to perform the averages and the averages themselves are discussed. Comparisons with the Standard Model (SM) are made, and SM parameters are determined.

2 Z lineshape and forward-backward asymmetries

Each LEP experiment analyses the interactions $e^+e^- \rightarrow \mathrm{hadrons}(\gamma)$, $\ell^+\ell^-(\gamma)$, where $\ell = e,\ \mu,\ \tau$, and (γ) denotes the possible presence of radiative photons. In a χ^2 fit to the hadronic and leptonic cross sections and leptonic forward-backward asymmetries, each experiment determines a set of 9 electroweak parameters describing the Z resonance [1,2]. These fits take correlations between the measurements into account, such as experimental systematic errors, theoretical errors (luminosity [3]), and the LEP centre-of-mass energy calibration [4].

The 9 parameters are: the mass and total width of the Z boson, $\mathrm{M_Z}$ and Γ_Z, based on a Breit-Wigner with s-dependent width; the hadronic pole cross section, $\sigma^\circ_\mathrm{had} \equiv \frac{12\pi}{\mathrm{M_Z^2}}\frac{\Gamma_e\Gamma_\mathrm{had}}{\Gamma_\mathrm{Z}\Gamma_\mathrm{Z}}$; the ratios of the pole cross sections for hadrons and leptons, or equivalently the ratio of the Z partial widths, $\mathrm{R}_\ell \equiv \sigma^\circ_\mathrm{had}/\sigma^\circ_\ell \equiv \Gamma_\mathrm{had}/\Gamma_\ell$; and the pole forward-backward asymmetry, $\mathrm{A^{\circ,\ell}_{FB}} \equiv \frac{3}{4}\mathrm{A_e A_\ell}$.

In order to average the four sets of Z parameters from the LEP experiments, the correlations between the experiments are needed. These inter-experimental correlations arise mainly from the common luminosity theory error of $\pm 0.11\%$ [3] and the common LEP energy calibration [4].

To extract these correlations, an approximate procedure based on the 9 parameters and their error matrix $\mathcal{E}$ is used [5]. A second fit is performed to the data set of an experiment, where all experimental errors not arising from the above correlations are halved, simulating the weight of four experiments in the average. Denoting with $\mathcal{E}'$ the error matrix of the second fit, the error matrix $\mathcal{C}$ describing the inter-experimental correlations is: $\mathcal{C} = (4\mathcal{E}' - \mathcal{E})/3$. To cross check this method for $\mathrm{M_Z}$ and Γ_Z, a fit to the complete set of hadronic cross sections, which essentially determine $\mathrm{M_Z}$ and Γ_Z, is performed. Good agreement is observed.

Not assuming lepton universality, the average has a χ^2/dof of 22/27. The results for R_ℓ and $\mathrm{A^{\circ,\ell}_{FB}}$ agree for the different species of charged leptons (Figure 1). Assuming lepton universality, the average has a χ^2/dof of 26/31, with [5]:

$$
\begin{array}{lcr}
\mathrm{M_Z} & = & 91186.3 \pm 2.0\ \mathrm{MeV} \\
\Gamma_\mathrm{Z} & = & 2494.6 \pm 2.7\ \mathrm{MeV} \\
\sigma^\circ_\mathrm{had} & = & 41.508 \pm 0.056\ \mathrm{nb} \\
\mathrm{R}_\ell & = & 20.778 \pm 0.029 \\
\mathrm{A^{\circ,\ell}_{FB}} & = & 0.0174 \pm 0.0010\ .
\end{array}
$$

The off-diagonal elements in the correlation matrix are less than 15%. The parameter $\mathrm{R}_\ell = \Gamma_\mathrm{had}/\Gamma_\ell$ is especially sensitive to the strong coupling constant $\alpha_\mathrm{S}(\mathrm{M_Z^2})$ (via QCD corrections to Γ_had) and rather insensitive to top and Higgs effects (as it is a ratio of partial widths). It allows to determine: $\alpha_\mathrm{S}(\mathrm{M_Z^2}) = 0.124 \pm 0.004 \pm 0.002(\mathrm{M_H})$, where the second error arises due to the variation of $\mathrm{M_H}$ from 60 GeV to 1 TeV.

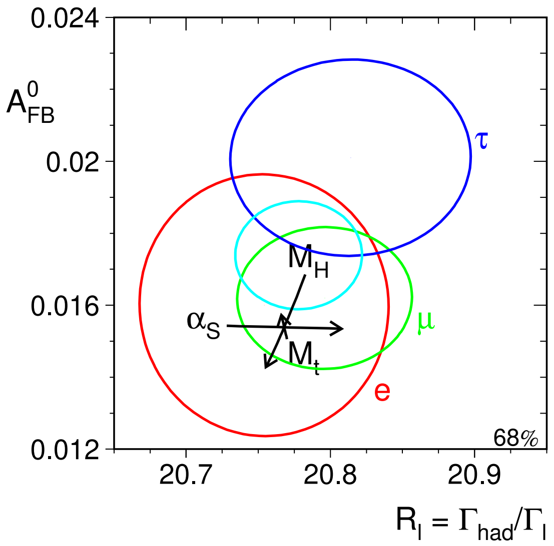

Figure 1: Contours of 68% probability in the $(R_\ell, A^{0,\ell}_{FB})$ plane with and without the assumption of lepton universality. The SM prediction is shown for $M_t = 175 \pm 6$ GeV, $M_H = 300^{+700}_{-240}$ GeV, $\alpha_S(M_Z^2) = 0.123 \pm 0.006$.

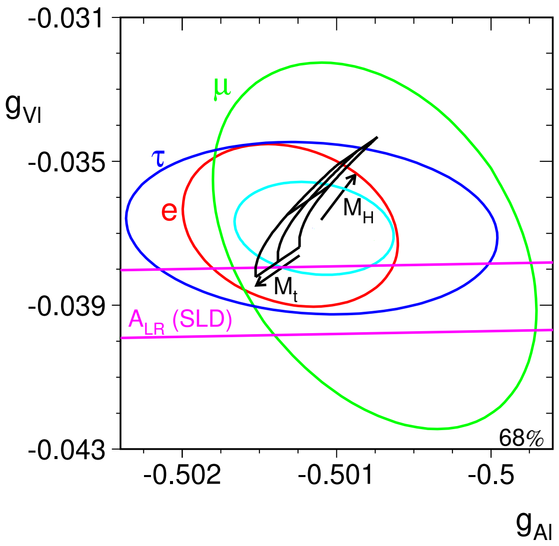

Figure 2: Contours of 68% probability in the $(g_{A\ell}, g_{V\ell})$ plane with and without the assumption of lepton universality derived from LEP data. Also shown is the one standard deviation band resulting from the A_{LR} measurement of SLD. The SM prediction is shown for $M_t = 175 \pm 6$ GeV, $M_H = 300^{+700}_{-240}$ GeV.

The partial widths of the Z are: $\Gamma_{had} = 1743.6 \pm 2.5$ MeV and $\Gamma_\ell = 83.91 \pm 0.11$ MeV, where Γ_ℓ is defined as the decay width into a pair of massless charged leptons. The partial width of the Z decay into invisible final states is: $\Gamma_{inv} = 499.5 \pm 2.0$ MeV. Within the SM, the invisible width arises from the Z decay into $\nu\bar{\nu}$ pairs. Hence it is possible to determine the number of light neutrino species: $N_\nu = (\Gamma_{inv}/\Gamma_\ell) \cdot (\Gamma_\ell/\Gamma_\nu)_{SM} = 2.989 \pm 0.012$. The error on N_ν is dominated by the 0.11% theory error on the luminosity measurement $(\delta N_\nu(\text{luminosity}) = \pm 0.008)$.

3 Polarisation asymmetries and effective coupling constants

In case of τ-pair production, the τ decay serves as a polarisation analyser allowing to measure the longitudinal τ polarisation, $\mathcal{P}_\tau$. As a function of the polar scattering angle $\cos\theta$, $\mathcal{P}_\tau$ is given by: $\mathcal{P}_\tau(\cos\theta) = -\frac{A_\tau(1+\cos^2\theta)+2A_e\cos\theta}{1+\cos^2\theta+2A_\tau A_e\cos\theta}$.

Each LEP experiment provides results for A_τ and A_e averaged over all τ-decay modes analysed [2]. The correlations between A_τ and A_e are negligible. The weighted averages are [5]: $A_\tau = 0.1401 \pm 0.0067$ and $A_e = 0.1382 \pm 0.0076$. The quantity A_e is also determined by the left-right polarisation asymmetry measured by SLD [6]: $A_{LR} = 0.1542 \pm 0.0037$, which is significantly higher than the LEP value of A_e. Using $A^{0,\ell}_{FB} = \frac{3}{4}A_e A_\ell$ and assuming lepton universality, another measurement of A_ℓ is derived: $|A_\ell| = 0.1523 \pm 0.0044$. The average of these 4 determinations of A_ℓ has a χ^2/dof of 6.2/3 (10%), with a value: $A_\ell = 0.1500 \pm 0.0025$.

The partial widths Γ_ℓ and the coupling parameters A_ℓ allow to access the effective coupling constants of the weak neutral current, $g_{V\ell}$ and $g_{A\ell}$, since: $A_\ell = 2\frac{g_{V\ell}/g_{A\ell}}{1+(g_{V\ell}/g_{A\ell})^2}$ and $\Gamma_\ell = \frac{G_F M_Z^3}{6\pi\sqrt{2}}[g_{V\ell}^2 + g_{A\ell}^2](1+\Delta_\ell^{QED})$. The sign of A_ℓ fixes the relative sign between $g_{V\ell}$ and $g_{A\ell}$. The absolute sign is fixed by the convention $g_{Ae} < 0$. The results are [5]: $g_{V\ell} = -0.03776 \pm 0.00062$ and $g_{A\ell} = -0.50108 \pm 0.00034$ (Figure 2).

4 Heavy Flavour results

The interesting parameters for electroweak physics in the heavy flavour sector are: $R_q \equiv \Gamma_q/\Gamma_{had}$, $A^{0,q}_{FB} \equiv \frac{3}{4}A_e A_q$ and for SLD in addition the left-right forward-backward asymmetry $A^{0,q}_{LR/FB} \equiv A_q$ where q stands for the heavy quark flavours b, c.

The averaging of heavy flavour results involves the most complicated procedure [7,8]. The reasons are that many results have common systematic errors, are dependent on each other and on additional model assumptions, such as decay models for heavy-quark mesons. The experiments agree on a common set of models and range of variation of their parameters. The shifts in the results due to these variations are determined and treated as correlated systematic errors. The dependencies on other electroweak parameters are parametrised explicitly, for example: $R_b^{updated} = R_b^{measured} + a_{R_c}\frac{R_c^{fit} - R_c^{used}}{R_c^{fit}}$. A χ^2 fit is performed, taking into account the explicit dependencies by comparing $R_b^{fit} \leftrightarrow R_b^{updated}$, and the correlated errors due to model parameters in the error matrix.

The results of the combination of the LEP and SLD measurements has a χ^2/dof of 51/74, with:

$$
\begin{aligned}
R_b &= 0.2178 \pm 0.0011 \\
R_c &= 0.1715 \pm 0.0056 \\
A_{FB}^{o,b} &= 0.0979 \pm 0.0023 \\
A_{FB}^{o,c} &= 0.0735 \pm 0.0048 \\
A_b &= 0.863 \pm 0.049 \\
A_c &= 0.625 \pm 0.084
\end{aligned}
$$

The largest correlation appears between R_b and R_c, with -23%: R_b depends on the value of R_c assumed in the R_b analyses. Other correlations are smaller than 12%.

5 The effective electroweak mixing angle

All asymmetries measured at LEP and SLD determine the ratio of $g_{V\ell}$ and $g_{A\ell}$, and thus a single parameter, the effective electroweak mixing angle, $\sin^2\bar{\theta}_W \equiv (1 - g_{V\ell}/g_{A\ell})/4$. The average of all $\sin^2\bar{\theta}_W$ measurements, Figure 3, has a rather large χ^2/dof of 12.8/6 (5%): The two most precise determinations of $\sin^2\bar{\theta}_W$, $A_{FB}^{o,b}$ and A_{LR}, are located on opposite sides of the average, which has a value of $\sin^2\bar{\theta}_W = 0.23165 \pm 0.00024$.

6 Constraints on the Standard Model

The precise electroweak measurements presented above are used to test the SM and constrain its parameters. For this analysis, the relevant SM parameters are the masses M_Z, M_W, M_H and M_t, and the coupling constants $\alpha_S(M_Z^2)$ and $\alpha(M_Z^2)$. The Fermi constant G_F replaces M_W. For the fine-structure constant $\alpha(M_Z^2)$ the value $1/(128.896 \pm 0.090)$ is used [9]. For the SM fits, the programs BHM [10], TOPAZ0 [11] and ZFITTER [12] are used.

The precision electroweak measurements of LEP and SLD are sensitive to electroweak radiative corrections. To leading order, these corrections are proportional to M_t^2 and to $\log(M_H/\mathrm{GeV})$.

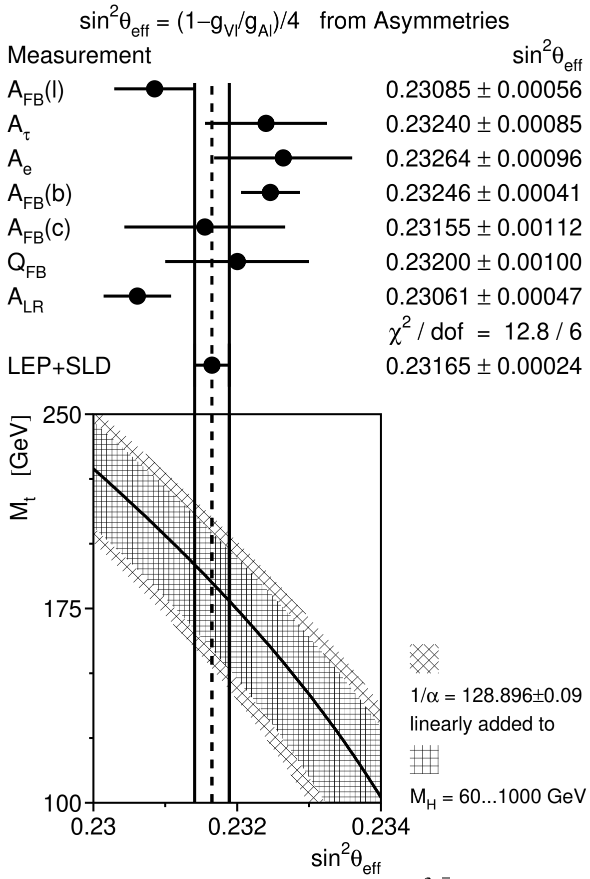

Figure 3: Determinations of $\sin^2\bar{\theta}_W$.

The results of the SM analysis of the LEP and SLD data are (Figure 4 top) [5]:

$$
\begin{aligned}
M_Z &= 91186.0 \pm 2.0\ \mathrm{MeV} \\
M_t &= 156 \pm 11\ \mathrm{GeV} \\
\log_{10} M_H &= 1.67^{+0.43}_{-0.33} \quad (25\text{–}130\ \mathrm{GeV}) \\
\alpha_S(M_Z^2) &= 0.1200 \pm 0.0032
\end{aligned}
$$

where the fit has a χ^2/dof of 18/11. The following parameters are derived from the LEP+SLD SM analysis [5]: $\sin^2\bar{\theta}_W = 0.23179^{+0.00023}_{-0.00026}$, $M_W = 80.337^{+0.042}_{-0.046}$ GeV, $1 - M_W^2/M_Z^2 = 0.2238^{+0.0009}_{-0.0008}$.

The prediction of M_t, through electroweak radiative corrections, agrees with the direct determination of M_t at the TEVATRON, $M_t = 175 \pm 6$ GeV [13]. Including this result, and also measurements of M_W ($\bar{p}p$) and $1 - M_W^2/M_Z^2$ (νN), one finds (Figure 4 bottom) [5]:

$$
\begin{aligned}
M_Z &= 91186.1 \pm 2.0\ \mathrm{MeV} \\
M_t &= 172 \pm 6\ \mathrm{GeV} \\
\log_{10} M_H &= 2.17 \pm^{+0.30}_{-0.35} \quad (70\text{–}300\ \mathrm{GeV}) \\
\alpha_S(M_Z^2) &= 0.1202 \pm 0.0033
\end{aligned}
$$

where the fit has a χ^2/dof of 19/14. The direct measurement of M_t moves the fitted M_H upwards.

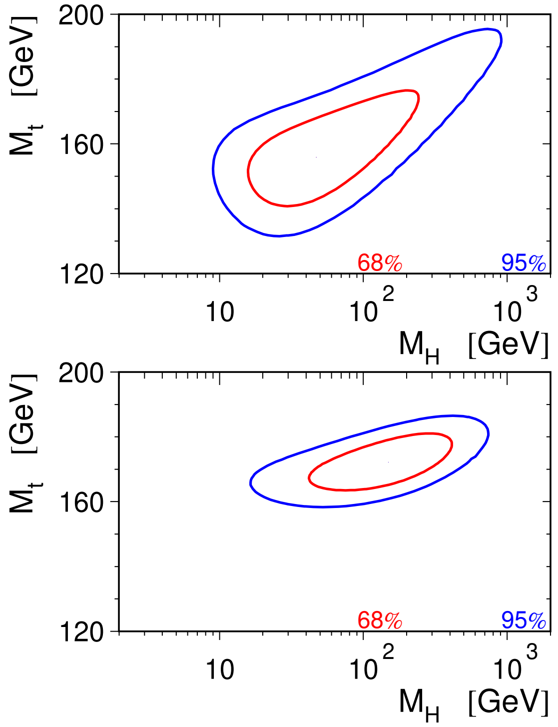

Figure 4: Contours of 68% and 95% probability in the (M_t, M_H) plane derived from the SM analysis. Top: LEP+SLD data. Bottom: all precision electroweak data.

The uncertainties arising due to the error in $\alpha(M_Z^2)$ are 0.00023 in $\sin^2\bar{\theta}_W$, saturating its error, 4 GeV in M_t, and 0.2 in $\log_{10} M_H$, which are included in the errors quoted above. The uncertainties due to missing higher order electroweak corrections are estimated to be 1 GeV in M_t and $0.1-0.2$ in $\log_{10} M_H$, which are not included in the errors quoted above. Further effort is needed in reducing the error on $\alpha(M_Z^2)$ (measurement of the hadronic cross section at low $\sqrt{s}$) and in the calculation of higher-order corrections affecting M_H. Including all errors, $M_H < 0.55$ TeV at 95% CL.

7 Discussion

The measurements of R_b and R_c were a problem for the SM in the past [14]. New measurements improve the agreement. The largest deviations in the SM analysis now arise from the measurements of A_{LR} (+2.2 standard deviations) and $A_{FB}^{o,b}$ (−2.0 standard deviations). Both asymmetries are statistically dominated measurements.

If they are excluded from the SM analysis, the central values of the fitted parameters are unchanged, whereas the errors are increased slightly. This is due to the fact that the effects compensate, as they pull in opposite direction. However, there is no indication of an experimental problem in these measurements which could justify their exclusion from the SM analysis.

8 Conclusions

The LEP-1 program is a great success: In 1993 and 1995, two precision scans of the Z lineshape were performed. In total, 16 million events for precision results were collected by the 4 LEP experiments. Beam polarisation at SLC allows SLD to perform the single most precise measurement of $\sin^2\bar{\theta}_W$.

Preliminary results from LEP+SLD determine M_Z, Γ_Z, $\sin^2\bar{\theta}_W$ and R_b with unprecedented accuracy. The measurements test the SM and its electroweak radiative corrections at the permille level. The prediction of M_t agrees well with the direct observation of top production at the TEVATRON. The prediction of M_H is self-consistent within the SM, $M_H < 0.55$ TeV at 95% CL.

Acknowledgement: It is a pleasure to thank my colleagues of the LEP electroweak working group; as well as E.Torrence for additional information on the SLD measurements.

References

1. E.Migliore, *these proceedings.*
2. R.Sobie, *these proceedings.*
3. S.Jadach, *these proceedings.*
4. G.Wilkinson, *these proceedings.*
5. The LEP collaborations and the LEP electroweak working group, in preparation.
6. E.Torrence, *these proceedings.*
7. The LEP experiments ALEPH, DELPHI, L3 and OPAL, CERN-PPE/96-017.
8. K.Mönig, *these proceedings.*
9. S.Eidelman, F.Jegerlehner, *Z. Phys.* C 67 (1995) 585.
10. G.Burgers et al., CERN yellow report 89-08.
11. G.Montagna et al., *Comp. Phys. Comm.* 76 (1993) 328.
12. D.Bardin et al., CERN-TH/6443-92.
13. P.Grannis, *these proceedings.*
14. The LEP collaborations and the LEP electroweak working group, CERN-PPE/95-172.