Electroweak Results from LEP

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to appear in the Proceedings of ICHEP92, Dallas, Aug. 6-12, 1992

Abstract

With 2 million Z^0 decay, LEP experiments at CERN have performed high precision test of electroweak theory. Preliminary results of 1990 and 1991 data are reported.

similar way.

INTRODUCTION

Each of 4 LEP experiments at CERN has accumulated nearly 500 thousand Z^0 decay, corresponding to the integrated luminosity of about 20 pb^{-1} , by the end of 1991. Since last publication of LEP data [1], significant improvements have been achieved in both LEP energy measurement with transverse beam polarization [2] and reduction of experimental systematic error [3].

LINESHAPE MEASUREMENT

The Z lineshape can be described as the convolution of the Breit-Wigner resonance cross section $\sigma^0(s)$ with initial-state radiation,

$$\sigma_{f\bar{f}}(s) = \int H(s, s') \sigma_{f\bar{f}}^0(s') ds', \quad (1)$$

where $H(s, s')$ is the initial-state radiator function. The peak cross section is expressed as,

$$\sigma_{peak}^0 = \frac{12\pi \Gamma_e \Gamma_f}{M_Z^2 \Gamma_Z^2}. \quad (2)$$

The lineshape of the lepton forward-backward asymmetry can be described in the

Fitting Method

The cross section measurement (line-shape) and lepton forward-backward asymmetry measurement were simultaneously fit. The fitting programs used are MIZA [4] for ALEPH and ZFITTER [5] for DELPHI, L3 and OPAL. Both programs agree well below the experimental accuracy.

The procedure was as follows.

- Each LEP experiment provides a set of most independent parameters,
 5 parameter ($M_Z, \Gamma_Z, \sigma_{had}^0, R_l, A_{FB}^0 \bar{l}l$)
 9 parameter ($M_Z, \Gamma_Z, \sigma_{had}^0, R_e, R_\mu, R_\tau, A_{FB}^0 e^+e^-, A_{FB}^0 \mu^+\mu^-, A_{FB}^0 \tau^+\tau^-$).
- Assign common systematic error among LEP experiments,
 $\Delta M_Z = 6.3 \text{ MeV}$ and $\Delta \Gamma_Z = 4.5 \text{ MeV}$ from LEP energy uncertainty,
 $\Delta \sigma_{had}^0 / \sigma_{had}^0 = 0.3\%$ from luminosity (theory).
- Construct 20×20 or 36×36 covariance matrix taking into correlated errors.

Table 1. Measured Z parameters by LEP experiments.

		ALEPH	DELPHI	L3	OPAL
M_Z	(GeV)	91.187 ± 0.009	91.188 ± 0.010	91.196 ± 0.010	91.180 ± 0.009
Γ_Z	(GeV)	2.501 ± 0.012	2.488 ± 0.012	2.495 ± 0.011	2.483 ± 0.012
σ_{had}^0	(nb)	41.60 ± 0.27	40.86 ± 0.28	40.95 ± 0.39	$41.01 \pm 0.41^*$
R_l		20.78 ± 0.13	20.82 ± 0.16	20.92 ± 0.16	20.87 ± 0.13
$A_{FB}^{0 l \bar{l}}$	(%)	1.54 ± 0.48	2.02 ± 0.59	2.64 ± 0.74	0.76 ± 0.48
R_e		20.69 ± 0.21	20.79 ± 0.28	21.24 ± 0.24	21.01 ± 0.26
R_μ		20.88 ± 0.20	20.92 ± 0.22	20.72 ± 0.27	20.65 ± 0.18
R_τ		20.77 ± 0.23	20.69 ± 0.30	20.63 ± 0.31	21.16 ± 0.25
$A_{FB}^{0 e^+ e^-}$	(%)	1.40 ± 0.93	1.3 ± 1.3	1.7 ± 1.4	-0.2 ± 1.2
$A_{FB}^{0 \mu^+ \mu^-}$	(%)	0.74 ± 0.72	1.48 ± 0.83	3.1 ± 1.0	0.47 ± 0.76
$A_{FB}^{0 \tau^+ \tau^-}$	(%)	2.69 ± 0.82	3.3 ± 1.0	2.8 ± 1.6	1.65 ± 0.82

* OPAL peak cross section is from 1990 data.

- Minimize $\chi^2 = \Delta^T \text{COV}^{-1} \Delta$ to obtain the best fit values.

The summary of measured Z parameters from each LEP experiments are given in Table 1, and combined results are given in Table 2, where the third column is the common systematic error among experiments due to LEP energy uncertainty and theoretical error on luminosity calculation. When combining the LEP data, additional common systematic errors due to t-channel subtraction in electron channel (0.5% of total t-ch subtraction) and due to LEP energy uncertainty effect on lepton forward-backward asymmetry (0.05%) were found to be negligible compared with experimental error, and thus were not taken into account.

The overall χ^2 was 17.2/15dof for 5 parameter fit (assuming lepton universality) and was 26.2/27dof for 9 parameter fit (no lepton universality).

Extracted Z Parameters

Due to the Standard Model constraint,

Figure 1. Contour plot of hadronic peak cross section versus R_l for combined LEP data together with the Standard Model prediction.

Table 2. Combined Z parameter from 4 LEP experiments.

	LEP	comm.	χ^2
M_Z (GeV)	91.187 ± 0.007	0.0063	2.3
Γ_Z (GeV)	2.492 ± 0.007	0.0045	1.5
σ_{had}^0 (nb)	41.16 ± 0.18	0.12	5.3
R_l	20.85 ± 0.07	—	0.5
$A_{FB}^0 l \bar{l}$ (%)	1.54 ± 0.27	0.05	5.5
$\Gamma_{l\bar{l}}$ (MeV)	83.33 ± 0.30	0.18	1.2
Γ_{had} (MeV)	1737 ± 7	3.8	
Γ_{inv} (MeV)	505 ± 6	3.1	
N_ν	3.04 ± 0.04	0.02	
$\alpha_s(M_Z^2)$	$0.135 \pm 0.009^*$	—	
R_e	20.92 ± 0.12	—	3.4
R_μ	20.79 ± 0.10	—	1.2
R_τ	20.84 ± 0.13	—	2.5
$A_{FB}^0 e^+e^-$ (%)	1.03 ± 0.58	0.05	1.5
$A_{FB}^0 \mu^+\mu^-$ (%)	1.20 ± 0.41	0.05	4.7
$A_{FB}^0 \tau^+\tau^-$ (%)	2.46 ± 0.48	0.05	1.7
Γ_e (MeV)	83.19 ± 0.36	0.18	
Γ_μ (MeV)	83.69 ± 0.53	0.18	
Γ_τ (MeV)	83.49 ± 0.63	0.18	

* The determination with Standard Model fit by assuming $N_\nu = 3$.

the strong coupling constant $\alpha_s(M_Z^2)$ measurement listed in Table 2 gives slightly better determination than determined from $R_l = \Gamma_{had}/\Gamma_{l\bar{l}}$ [6],

$$\alpha_s(M_Z^2) = 0.130 \pm 0.012. \quad (3)$$

These values are about 1.5σ higher than those determined with event shape analysis.

The number of light neutrino species N_ν is given by assuming lepton universality as,

$$N_\nu = \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{l\bar{l}}} \right)_{SM}^{-1} \cdot \left\{ \sqrt{\frac{12\pi R_l}{M_Z^2 \sigma_{had}^0}} - R_l - 3 \right\}, \quad (4)$$

where the Standard Model prediction is $\Gamma_{\nu\bar{\nu}}/\Gamma_{l\bar{l}} = 1.993 \pm 0.004$. The result is consistent with $N_\nu = 3$ as shown in Figure 1.

ASYMMETRY MEASUREMENT

The effective vector and axial-vector coupling is defined as,

$$\begin{cases} g_V(M_Z^2) = g_A(M_Z^2) (1 - 4 \sin^2 \theta_W^{\text{eff}}), \\ g_A(M_Z^2) = -\frac{1}{2} \sqrt{\rho^{\text{eff}}}, \end{cases} \quad (5)$$

where the effective electroweak mixing angle $\sin^2 \theta_W^{\text{eff}}$ is defined with vector and axial-vector effective coupling of electron as,

$$\sin^2 \theta_W^{\text{eff}} = \frac{1}{4} \left(1 - \frac{g_V}{g_A} \right). \quad (6)$$

The lepton forward-backward asymmetry, tau polarization, tau polarization forward-backward asymmetry, b-quark charge asymmetry and leptonic partial width can be expressed in terms of effective coupling constant as,

$$\begin{aligned} A_{FB}^0 l \bar{l} &= \frac{3}{4} A_e A_l, \\ P_\tau &= -A_\tau, \\ P_\tau^{FB} &= -\frac{3}{4} A_e, \\ A_{FB}^0 b \bar{b} &= \frac{3}{4} A_e A_b, \\ \Gamma_{l\bar{l}} &= \frac{G_F M_Z^3}{6\pi\sqrt{2}} \cdot (g_V^2 + g_A^2) \cdot \left(1 + \frac{3}{4} \frac{\alpha}{\pi} \right), \end{aligned} \quad (7)$$

Table 3. Effective $\sin^2 \theta_W^{\text{eff}}$.

	LEP Avr.	$\sin^2 \theta_W^{\text{eff}}$
$A_{FB}^0 \ell \bar{\ell}$	0.0154 ± 0.0027	0.2320 ± 0.0016
P_τ	-0.140 ± 0.018	0.2324 ± 0.0023
P_τ^{FB}	$-0.092 \pm 0.023^*$	0.2346 ± 0.0039
$A_{FB}^0 b \bar{b}$	0.098 ± 0.011	0.2324 ± 0.0020
Asymmetry Average		0.2324 ± 0.0011
Lineshape $\Gamma_{\ell \bar{\ell}}$		0.2334 ± 0.0011

* Only ALEPH data were used.

where $A_f = 2g_V g_A / (g_V^2 + g_A^2)$.

All the asymmetry data are evaluated at M_Z . The deconvolution of the initial- and final-state QED/QCD radiative correction, subtraction of γZ and pure γ term are performed for all data. The effective electroweak mixing parameter $\sin^2 \theta_W^{\text{eff}}$ was extracted from combined LEP measurement for various asymmetry data as shown in Table 3 together with $\sin^2 \theta_W^{\text{eff}}$ from leptonic partial width. The effective electroweak coupling from lineshape has been extracted by using the formula,

$$\Gamma_{\ell \bar{\ell}} = (1 + \kappa^{\text{eff}}) \cdot \frac{\alpha(M_Z^2) M_Z}{48 \sin^2 \theta_W^{\text{eff}} \cos^2 \theta_W^{\text{eff}}} \times \left[1 + (1 - 4 \sin^2 \theta_W^{\text{eff}})^2 \right] \left(1 + \frac{3\alpha}{4\pi} \right) (8)$$

where $\kappa^{\text{eff}} = 0.0040 \pm 0.0020$ is the effective parameter which absorbs the running Z self-energy. The same error is obtained with all asymmetry data and with leptonic partial width.

Lepton Universality

To test the lepton universality of the neutral current, the lineshape, lepton forward-backward asymmetry, tau polarization and tau polarization forward-backward asymme-

Table 4. Effective vector and axial-vector coupling constants.

flavour	$g_V(M_Z^2)$	$g_A(M_Z^2)$
e	-0.035 ± 0.005	-0.4991 ± 0.0011
μ	-0.029 ± 0.011	-0.5010 ± 0.0017
τ	-0.038 ± 0.004	-0.4998 ± 0.0019
1	-0.0352 ± 0.0025	-0.4995 ± 0.0009

try have been combined for all LEP data to determine effective leptonic vector and axial-vector coupling. The result is given in Table 4, and shown in Figure 2. The axial-vector coupling is determined by leptonic partial width, while asymmetry data measure the ratio $g_V(M_Z^2)/g_A(M_Z^2)$. Basically, the error on electron is $\sqrt{2}$ times smaller than others due to the existence of the eeZ coupling in both initial and final state. It also benefits from P_τ^{FB} measurement which is the measure of A_e . For tau, significant improvement is achieved for g_V determination through tau polarization measurement.

When converted into the coupling ratio with respect to electrons, one gets,

$$\begin{aligned} \frac{g_{V\mu}}{g_{Ve}} &= 0.83^{+0.42}_{-0.31}, \\ \frac{g_{V\tau}}{g_{Ve}} &= 1.10^{+0.22}_{-0.18}, \\ \frac{g_{A\mu}}{g_{Ae}} &= 1.0037 \pm 0.0040, \\ \frac{g_{A\tau}}{g_{Ae}} &= 1.0013 \pm 0.0042, \end{aligned} \quad (9)$$

thus one observes that the lepton universality for neutral current holds at 0.4% level.

STANDARD MODEL FIT

By assuming the Standard Model, one determines the top mass through the electroweak radiative corrections. Since LEP-I

Figure 2. The effective vector and axial-vector coupling. The dashed line is the result with assuming lepton universality. The Standard Model with $M_{Higgs} = 300$ GeV is also shown for various top mass.

data alone cannot determine Higgs mass, one normally fix the Higgs mass. Additional constraint can be superimposed by using $\alpha_s(M_Z^2)$ measurement with event shape at LEP.

When M_{Higgs} is fixed at 300 GeV, and $\alpha_s(M_Z^2)$ is treated as free parameter, combining all the LEP data gives,

$$M_{top} = 139^{+24}_{-29} + 19(M_H = 1TeV) - 23(M_H = 50GeV) \text{ GeV}$$

$$\alpha_s(M_Z^2) = 0.135 \pm 0.009 \pm 0.002(M_H) \quad (10)$$

where $\chi^2 = 2.6/5\text{dof}$.

If one perform the constraint fit with $\alpha_s(M_Z^2)$ determined from event shape analysis $\alpha_s(M_Z^2) = 0.120 \pm 0.006$ [6], one gets

$$M_{top} = 148^{+22}_{-26} + 19(M_H = 1TeV) - 23(M_H = 50GeV) \text{ GeV}$$

$$\alpha_s(M_Z^2) = 0.125 \pm 0.005 \pm 0.002(M_H) \quad (11)$$

where $\chi^2 = 4.8/6\text{dof}$. This fit also yields a

Figure 3. The parameter S and T determined from LEP data alone.

determination of $\sin^2 \theta_W^{\text{eff}}$ and M_W as,

$$\sin^2 \theta_W^{\text{eff}} = 0.2328 \pm 0.0007$$

$$M_W = 80.17^{+0.14}_{-0.15} \text{ GeV} \quad (12)$$

Oblique Electroweak Correction

To probe the physics beyond the Standard Model, the fit for S and T parameter has been performed [7]. With LEP data alone, the parameter U is irrelevant. All the LEP data (alone) were used to fit S, T and $\alpha_s(M_Z^2)$ with the constraint on $\alpha_s(M_Z^2)$ measured with event shape analysis at LEP. From the Z line-shape measurement, information of total and partial width (Γ_Z , Γ_{ll} and Γ_{had}) was used with correlation between them taken into account. The reference point was taken at $M_{top} = 150$ GeV and $M_{Higgs} = 1$ TeV. The conservative error was assigned for strong coupling constant as $\alpha_s(M_Z^2) = 0.120 \pm 0.010$. This con-

straint fit yields,

$$\begin{cases} S &= -0.42 \pm 0.45 \\ T &= -0.19 \pm 0.41 \\ \alpha_s(M_Z^2) &= 0.126 \pm 0.007 \end{cases} \quad (13)$$

with $\chi^2 = 2.3/5\text{dof}$. The result is shown in Figure 3, where technicolor model is also shown. Both S and T are consistent with zero on the contrary to the previous 1990 result when negative S was preferred [7].

CONCLUSION

The high precision test of the electroweak theory has been performed at LEP with typically 0.4% accuracy. No significant deviation from the Minimal Standard Model. Although LEP-I alone has no sensitivity for Higgs mass determination, the top mass has been determined to $\pm 20\%$ accuracy with LEP data.

As for the perspectives for future measurements, the LEP energy uncertainty could be reduced to the order of 3 MeV for Z mass and total width if one perform the energy scan again and measure the beam polarization at $M_Z \pm 2$ GeV. With more statistics, each experiment is expected to reduce its systematic error. Asymmetry data are still statistically dominated. These measurements can be further improved with forthcoming data in 1992.

I would like to thank colleagues from LEP electroweak working group who worked for the results presented in this paper. I had largely appreciated discussions and suggestions from my colleagues in ALEPH, Alain BLONDEL, Manel MARTINEZ and Gigi ROLANDI. I also would like to thank Michael E. PESKIN for helpful discussions.

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