The First Year of OPAL on Z°

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Abstract

Since its first observation of the Z° at LEP last August, the OPAL detector has collected 112k hadronic decays and 11k leptonic decays of the Z° at center-of-mass energies between -3GeV and +4GeV of the Z° peak, by July, 1990. Based on measurements of total cross sections and forward-backward asymmetries of these decay modes, the mass of the Z° boson, its total width, its partial widths into hadrons and leptons, and its invisible width (or the number of neutrinos) were determined in a model-independent way. The result was compared to the Standard Model predictions. In the framework of the Standard Model, the effective weak mixing angle was obtained from the data. Finally implication on the top quark mass was discussed.

1 OPAL

The OPAL Collaboration consists of about 300 physicists from 24 institutes in 9 different countries. The OPAL detector [1] is a general purpose detector situated at the CERN e+e− collider LEP. Trajectories of charged particles are measured by a jet chamber, a large volume drift chamber with 159 layers of wires in each of its 21 azimuthal sectors, together with a vertex detector and a z-chamber, with a momentum resolution of Δp/p = 10% at p ≈ 45GeV/e. Outside the tracking chambers is a solenoidal coil, a time-of-flight counter array, and an electromagnetic calorimeter, which measures electromagnetically showering particles with its 11,704 lead glass blocks and a pre-sampler, with an energy resolution of ΔE/E = 3% at E ≈ 45GeV. An instrumented magnet return yoke serves as a hadron calorimeter, surrounded by four layers of outer muon chambers. Forward detectors measure the luminosity of LEP.

Here we report an improved measurement of the properties of the Z° boson by the OPAL detector, based on a higher statistics data and smaller systematic errors than the previous publications [2,3,4]. The analysis presented here was based on the 123k Z° events collected by July 25,1990.

2 Measurements of Z° Boson

Luminosity measurement by the forward calorimeter and the proportional tube chambers [3] has improved as the geometrical acceptance was better surveyed and the analysis and the calibration procedure were refined. Also, an independent measurement of the absolute luminosity by a set of scintillation counters became available. As a result, the systematic normalisation error has decreased to 1.6% and the fill-to-fill systematic error to 0.8%.

Hadronic decays of the Z°, which have many charged and neutral hadrons in the final state, were selected by requiring a large number of energy clusters and a large energy deposit in the electromagnetic calorimeter. An acceptance of 97.7% was achieved with a background fraction of 0.4 - 0.5% due to τ+τ− events and two-photon multihadronic events. Selection based on charged tracks was also made, and agreement within better than 1% was observed. The systematic error was estimated to be 0.77%, which included the fragmentation uncertainty of 0.50%.

For the selection of leptonic decays of the Z°, multihadronic events were efficiently rejected by requiring a low multiplicity in the event.

e+e− decays of the Z° were selected by identifying at least two high energy electromagnetic clusters associated with charged tracks. After the 10° acollinearity angle cut, the selection efficiency was found to be 99.5% within the angular acceptance of |cos θe−| < 0.7, with a 1.0% systematic error.

Events were classified as μ+μ− candidates if they contained at least two muons, which were identified redundantly by the muon chamber, the hadron calorimeter, and the electromagnetic calorimeter. Cosmic ray events were rejected by time-of-flight measurements and track vertex re-
quirements. With a geometrical acceptance extended to $|\cos\theta| < 0.95$, the selection efficiency became 90.8% with an estimated systematic error of 0.9%.

$\tau^+\tau^-$ events were identified as events with two low-multiplicity jets of particles. While total energy cuts efficiently discriminated $e^+e^-$ events, events accepted by the $\mu^+\mu^-$ selection were rejected. With a 15° acollinearity cut between the jets and an acceptance cut of $|\cos\theta| < 0.9$, the selection efficiency of 73.9% was obtained. The total systematic error was estimated to be 1.9%.

For measurements of forward-backward asymmetries, leptonic decays in which both leptons were assigned the same charge were not used. Such events amounted to only 1.0-1.6% of the selected sample: the probability for double assignment of the wrong charge was thus negligible.

$b\bar{b}$ final states were extracted out of the hadronic sample by tagging decay leptons. The measured rate of such events, together with our measurement of the total hadronic width (see the following sections), was used to obtain the partial width of $b$ quarks (Table 1). Forward-backward charge asymmetry of $b\bar{b}$ events was also measured by using the charge of the tagged leptons. A more detailed account of this measurement can be found in [5].

Final state radiation in hadronic decays of the $Z^0$ was first observed by our group [6]. Our measured total hadronic width, together with an updated measurement of final state radiation, allowed a determination of the partial widths of up and down type quarks [5]. The result was listed in Table 1.

The results of the measurements of cross sections and forward-backward asymmetries are shown in Figures 1-3, together with the previous measurements by the low energy experiments. They are also shown in Figures 5 and 6. Also indicated in Figure 1 was our measurement of the $e^+e^- \rightarrow \gamma \gamma$ cross section.

3 Analysis

The uncertainties in the LEP energy scale were $\pm 27$ MeV for the 1989 run and $\pm 24$ MeV for the 1990 run. They were decomposed into a part fully correlated for the 1989 and the 1990 data ($\pm 17$ MeV) and an additional uncorrelated part ($\pm 21$ MeV and $\pm 17$ MeV for 1989 and 1990 respectively).
These errors and their correlations were taken into account in the fits.

Radiative corrections significantly modify the cross sections and forward-backward asymmetries. For the calculation of the cross sections of $qar{q}$, $\mu^+\mu^-$, and $\tau^+\tau^-$ processes, the program ZFITTER [7] was used. Photonic corrections included in this program were a complete $O(\alpha)$ calculation, leading $O(\alpha^2)$, and the exponentiation of soft photons. The calculated total cross sections agreed with that obtained from the program ZSHAPE [8] to better than 0.2%. The effects of cuts on the differential cross section reproduced the results obtained with the KORALZ program [9] to better than 0.5% over the energy range of interest.

The presence of $t$-channel exchange diagrams in the $e^+e^-\rightarrow e^+e^-\gamma$ process, which were not included in the ZFITTER calculation, complicates the treatment of this process. Recently a new calculation for this process has become available in the form of the program ALIBABA [10]. It included contributions from lowest order and all one-loop and box diagrams. Photonic corrections were treated exactly to first order with a leading log summation for higher order terms. The ALIBABA program was unfortunately too slow to be used in the fits. Therefore we used it to calculate the contributions of the $t$-channel exchange and $s$-$t$ interference terms for the $e^+e^-$ process, and they were subtracted from the measured cross sections and asymmetries ("$t$-channel subtraction"). The resulting cross sections and asymmetries were then considered as a pure $s$-channel process, and the ZFITTER was used to fit them.

As a check to the ALIBABA calculation, the $t$-channel subtraction procedure was repeated for different angular ranges and the fit results were compared; the observed changes were consistent with statistical fluctuations. We assigned a 5% systematic error to the $t$-channel subtraction, inflated from the 0.5% uncertainty quoted in [10], which is still negligible compared to the current statistical errors.

### 3.1 Hadronic Line Shape

A model independent fit with the mass $M_{Z}$, the width $\Gamma_{Z}$, and the peak cross section $\sigma_{had}^{pole}$ was performed to the hadronic cross sections. The result was $M_{Z} = 91.164 \pm 0.011 \pm 0.021$ GeV/c$^2$, $\Gamma_{Z} = 2.496 \pm 0.021$ GeV, and $\sigma_{had}^{pole} = 41.88 \pm 0.74$ nb with $\chi^2/ndf = 8.9/13$. The second error on $M_{Z}$ was due to the LEP beam energy uncertainty.

![Figure 4: Hadronic line shape compared with the Standard Model predictions for $N_{\nu} = 2, 3, 4$.](image)

Figure 4 compares our result with the Standard Model predictions; it was totally compatible with the Standard Model with the number of light neutrinos $N_{\nu} = 3$, and the possibility of $N_{\nu} = 2$ or 4 looked completely abandoned.

### 3.2 Leptonic Data - Combined Fits

Both the cross sections and the charged asymmetries of the leptonic decays were used to extract the partial widths of the $Z^0$ boson. In all of the following fits, if not explicitly mentioned, the hadronic cross sections were also used in order to account properly for the correlated errors with $M_{Z}$, $\Gamma_{Z}$, and the hadronic partial width, $\Gamma_{had}$, which were also treated as free parameters in the fits.

The differential cross section for $s$-channel fermion-pair production can be expressed as:

$$\frac{d\sigma}{dc} \propto (C_{\gamma\gamma} + C_{ZZ} |\chi|^2) (1 + c^2) + (A_{ZZ} |\chi|^2 + A_{Z} \text{Re} \chi) c$$

where $c = \cos \theta$ and $\chi \propto s/(s - M_{Z}^2 + i\Gamma_{Z}/M_{Z})$. Here only the dominant terms were indicated. The most dominant $C_{ZZ}$ determines the total cross sections. While the forward-backward asymmetry at the $Z^0$ resonance is determined by $A_{ZZ}/C_{ZZ}$, the
ratio $A_{\tau} \text{Re} \chi/(|C_{ZZ}|^2)$ describes the energy evolution of the asymmetry. These coefficients are simply related to the vector and axial vector couplings of the $Z^0$ to the fermion at tree level. Higher order corrections, however, modify this relationship in a model-dependent way. We used our measurements of leptonic final states to determine these coefficients without any presumed relation.

In the fit, we parametrized the coefficients in terms of the effective leptonic coupling constants, $\hat{a}_1^2 \hat{v}_1^2$ and $\hat{a}_2^2$, and the partial widths of the leptons, $\Gamma_{\ell^{+}\ell^{-}}$, in the following way:

$$C_{ZZ} \propto \Gamma_{\ell^{+}\ell^{-}} \; , \; \tilde{A}_{ZZ} \propto \hat{a}_1^2 \hat{v}_1^2 \; , \; A_{\tau} \propto \hat{a}_2^2 \; ,$$

and they were treated as completely independent. The fit resulted in $\Gamma_{\ell^{+}\ell^{-}} = 82.7 \pm 1.3$ MeV, $\Gamma_{\mu^{+}\mu^{-}} = 85.9 \pm 2.0$ MeV, $\Gamma_{\tau^{+}\tau^{-}} = 83.9 \pm 2.3$ MeV, $\hat{a}_1^2 \hat{v}_1^2 = 0.0036 \pm 0.0004$, and $\hat{a}_2^2 = 0.98 \pm 0.13$, with $\chi^2/ndf = 68.4/83$, fully consistent with the principle of lepton universality, and also with the Standard Model prediction.

With the assumption of lepton universality, the fit yielded $\Gamma_{\ell^{+}\ell^{-}} = 83.6 \pm 1.0$ MeV with $\chi^2/ndf = 70.2/86$. At the same time, $M_Z = 91.174 \pm 0.011$ GeV/c$^2$, $\Gamma_{Z^0} = 2.505 \pm 0.020$ GeV, and $\Gamma_{\text{had}} = 1.778 \pm 0.026$ GeV were obtained from the fit. The curves drawn in Figures 1, 2, 5, and 6 were the fit result. It is evident from the figures that the fit result described the whole spectrum of the $e^{+}e^{-}$ reaction pretty well. In fact, it described not only the line shapes and the asymmetries but also the differential cross sections as well (Figure 7).

The same fit also gave a model-independent determination of the invisible width of the $Z^0$, $\Gamma_{\text{inv}}$, to be $476 \pm 25$ MeV, and the number of the light neutrino species (or the number of generations), $N_{\nu} \equiv \Gamma_{\text{inv}}/\Gamma_{\nu}$, to be $2.86 \pm 0.15_{-0.04}^{+0.02}$, where the second errors came from the uncertainties in $m_{\text{top}}, m_{H}$, and $\alpha_S$ ($m_{\text{top}} = 50 - 250$ GeV/c$^2$, $m_{H} = 20 - 1000$ GeV/c$^2$, $\alpha_S = 0.09 - 0.15$). The ratio of the hadronic and the leptonic partial widths was $R_Z \equiv \Gamma_{\text{had}}/\Gamma_{\ell^{+}\ell^{-}} = 21.26 \pm 0.32$, which should be compared to the Standard Model prediction of $20.6 - 21.1$ where the uncertainties in $m_{\text{top}}, m_{H}$, and $\alpha_S$ were taken into account.

The differential cross section can be also expressed directly in terms of $\hat{a}_1^2$ and $\hat{v}_1^2$ in the form of the improved Born approximation [11], in which the tree level relationship among the coefficients, $C_{ZZ}$, $\tilde{A}_{ZZ}$, and $A_{\tau}$, was assumed (i.e., $\Gamma_{\ell^{+}\ell^{-}} \propto \hat{a}_1^2 + \hat{v}_1^2$ etc.). A fit using this parametrization yielded a very precise determination of the couplings: $\hat{a}_1^2 = 1.005 \pm 0.012$ and $\hat{v}_1^2 = 0.0038 \pm 0.0033$ with $\chi^2/ndf = 70.2/86$, in a good agreement with other measurements [12].

The effective couplings may be written in terms of $\rho_Z$ and the effective weak mixing angle $\sin^2 \theta_W$ by

$$\hat{a}_1^2 \to \rho_Z \; , \; \hat{v}_1^2 \to \rho_Z (1 - 4 \sin^2 \theta_W)^2 \; .$$
In this parametrization, the $p_X$ parameter mainly determines the total cross section while $\sin^2 \theta_W$ describes the asymmetry. A fit treating $p_X$ and $\sin^2 \theta_W$ as independent parameters yielded $p_X = 1.005 \pm 0.012$ and $\sin^2 \theta_W = 0.2315 \pm 0.0028$, as shown in Figure 8, if the $\chi^2$ minimum for $\sin^2 \theta_W < 0.25$ was chosen. With the minimal Standard Model relationship between $p_X$ and $\sin^2 \theta_W$ imposed (indicated as a line in Figure 8), the fit resulted in a more precise determination of the effective weak mixing angle, $\sin^2 \theta_W = 0.2315 \pm 0.0028$.

### 3.3 Top Quark Mass

Within the framework of the minimal Standard Model, our data were used to constrain the top quark mass, $m_{\text{top}}$.

A fit to the OPAL measurements of the line shapes and the asymmetries resulted in the central value of $m_{\text{top}} = 154 \text{GeV}/c^2$. On the other hand, if our measured value of $M_Z$ was used together with the $M_W/M_Z$ values measured by the UA2 and the CDF experiments, $m_{\text{top}} = 143 \text{GeV}/c^2$ was obtained. Both values, which could be considered as independent estimates of $m_{\text{top}}$, coincided within $\approx 10 \text{GeV}/c^2$, strongly suggesting that $m_{\text{top}}$ lie around that region.

By combining our measurements of line shapes and asymmetries and the $M_W/M_Z$ measurements, we obtained $m_{\text{top}} = 141^{+35}_{-20} \text{GeV}/c^2$, where uncertainties in $\alpha$ of $\pm 0.02$ and in $m_H$ of $40 - 1000 \text{GeV}/c^2$ were taken into account.

### 4 Summary

We measured the cross sections and the forward backward charge asymmetries of various $Z^0$ decays with the OPAL detector. Using these measurements, we determined the properties of the $Z^0$, such as the mass, the width, and the couplings to the various fermions (Table 1). Their agree-
ments with the Standard Model predictions were impressive. Our model-independent determination of the invisible width of the \( Z^0 \) constrained the number of generations to be \( 2.86 \pm 0.15 \).

In the context of the minimal Standard Model, the weak mixing angle, \( \sin^2 \theta_W \), was determined to be \( 0.2315 \pm 0.0028 \). The top quark mass evaluated from our data agreed with that obtained from the \( M_W/M_Z \) measurements at the \( pp \) colliders and our \( M_Z \) value, indicating \( m_{\text{top}} \) be as high as \( \approx 150 \text{GeV}/c^2 \). Finally, combining our data and the \( M_W/M_Z \) measurements yielded \( m_{\text{top}} = 144^{+50}_{-50} \text{GeV}/c^2 \).

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References


Table 1: A summary of OPAL results. 123\( k \) \( Z^0 \) events collected by July 25, 1990 were used in the analysis. The second error of \( M_Z \) was due to the LEP energy uncertainty.