

A Measurement of Z^0 Mass and Width with the OPAL Detector at LEP

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Abstract: We report a measurement of the mass and total width of the Z^0 boson, based on 25,801 hadronic decays selected over eleven energy points between 88.28 and 95.04 GeV. We obtain a mass of $M_z = 91.145 \pm 0.022(exp) \pm 0.030(LEP)$ GeV, and a total width of $\Gamma_z = 2.526 \pm 0.047$ GeV.

1 Introduction

We present here a measurement [1] of the hadronic decays of the Z^0 , based on the entire data sample collected in 1989 with the OPAL detector.

The cross sections were measured at 11 centre-of-mass energies between 88.28 and 95.04 GeV by repeatedly scanning across the Z^0 resonance. Measurements at nearby energies, within 10 MeV, were combined into one data point at the luminosity-weighted average energy. The LEP fractional error in the energy of each beam was $3 \cdot 10^{-4}$, corresponding to 30 MeV in the centre-of-mass energy. The point-to-point fractional error in the energy was $1 \cdot 10^{-4}$.

2 The OPAL Detector

The data were recorded with the OPAL detector [2] at the CERN e^+e^- collider LEP. The detector consists of a set of large volume drift chambers (vertex detector, jet chamber, z -chamber) positioned inside a solenoidal coil, which is surrounded by time-of-flight counters, an electromagnetic calorimeter with a presampler, an instrumented magnet return yoke serving as a hadron calorimeter and four layers of muon chambers. The electromagnetic calorimeter consists of a cylindrical array and two endcaps of lead glass blocks, covering the region $|\cos(\theta)| < 0.98$. Each block subtends a solid angle of approximately 40×40 mrad². The blocks in the barrel region project towards the interaction point. The time-of-flight system (TOF) covers the region $|\cos(\theta)| < 0.82$. Small angle Forward Detectors serve as a luminosity monitor.

For Monte Carlo studies the OPAL detector was simulated using a computer program [3] which includes the detector geometry and material as well as effects of resolution and efficiencies.

3 The Luminosity Measurement

The integrated luminosity of the colliding beams was determined by the measurement of small angle Bhabha scattering, a process insensitive to Z^0 effects. The measurement used the forward detector, consisting of two identical elements placed around the beam pipe at either end of the central tracking chambers. In this analysis two components of this detector were used in a complementary manner: (i) a calorimeter provided a high statistics measurement of the relative luminosity at each beam energy; (ii) a set of proportional tube chambers with a well defined geometry and acceptance provided the absolute luminosity calibration.

Each calorimeter consists of a cylindrical lead-scintillator sandwich divided into 16 azimuthal segments and two longitudinal sections: a presampler of 4 radiation lengths (X_0), and a main calorimeter of 19 X_0 . For 45 GeV electrons, the energy resolution of the calorimeter was measured to be 1.3 GeV ($19\%\sqrt{E}$), with 84% of the energy deposited in the main calorimeter. Light sharing between adjacent segments and between inner and outer readouts of the main calorimeter was used to determine the center of the showers. The polar angle resolution varied between 1 and 10 mrad, being best near the inner edge of the calorimeter, while the resolution in azimuth varied between 3.5 and 35 mrad, being best at the segment boundaries. The acceptance of the calorimeter extends from 39 to 155 mrad, and is essentially complete in azimuth.

The proportional tube chambers are positioned between the presampler and main sections of the calorimeter. These chambers each consist of a vertical, horizontal, and diagonal plane of proportional tubes [4] of 1 cm^2 cross section. The positions of the centroids of showers from incident electrons or photons are measured using the pulse height information from the tubes. For 45 GeV electrons, the tube chambers have 1.3 mrad resolution in θ and ϕ and detect 99.3% of the showers. The tube chamber acceptance extends from 50 mrad to 135 mrad in polar angle, and covers 95% in azimuth. The positions of the tube chambers were surveyed to 1.0 mm and were checked with electron tracks measured in drift chambers [5] in front of the calorimeter.

To select events for the absolute luminosity calibration a fiducial region was defined well within the tube chamber and calorimeter acceptance, extending from 58 mrad to 124 mrad in polar angle from the nominal beam axis, and excluding azimuthal angles within 10 degrees of the horizontal and vertical planes. Particles emitted from the interaction point in this angular region traversed only a minimum of material before reaching the forward detectors (less than $0.2 X_0$). The average of the angles measured on the two sides of the event was required to lie within this fiducial region. Therefore the acceptance was largely independent of the position and size of the beam intersection region. To reject background due to off-momentum beam particles, the difference in the azimuthal angles between the two ends, $\Delta\phi$, was required to be in the range between 160° and 200° . Finally, the average of the energies of the largest cluster in each calorimeter was required to be larger than $2/3$ of the beam energy. One quadrant of the tube chambers was not used since one segment in the corresponding calorimeter region was defective.

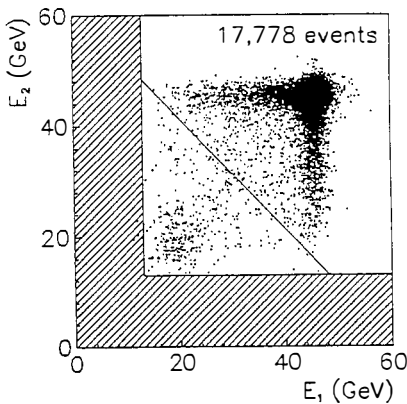


Figure 1: The energies measured in the two forward calorimeters, E_1 vs E_2 , for luminosity event candidates passing the tube chamber selection cuts. The shaded region is excluded by the trigger requirement that at least 12 GeV be deposited in opposite calorimeter segments. Events in the region above the diagonal satisfy the requirement that $2/3$ of the centre-of-mass energy is observed in the calorimeter.

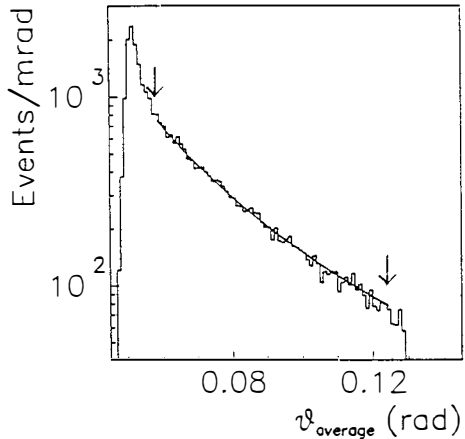


Figure 2: Angular distribution of luminosity event candidates, as measured by the tube chambers. The arrows show the boundaries of the fiducial region, inside of which the data follow the expected $1/\theta^3$ distribution, shown by the curve.

The detector read-out was triggered when the energy sum in each forward calorimeter exceeded 15 GeV overall, or 12 GeV in back-to-back clusters. The overall trigger efficiency was found to be $99.0 \pm 0.3\%$ for the events selected by these cuts. Figure 1 shows the energies measured in the two calorimeters for all events prior to the energy cut. The vertical and horizontal arms of the distribution correspond to radiative events in which one photon escapes undetected. A correction of 0.55%, with an uncertainty of 0.5%, was applied to account for the events that had a low measured energy at both ends of the detector. Most of these events were found to be small angle Bhabha events in which the electrons were outside the tube chamber acceptance but had showered into the fiducial volume.

The BABAMC Monte Carlo program [6] was used to generate $e^+e^- \rightarrow e^+e^-(\gamma)$ events, distributed at various energies across the Z^0 resonance. A Gaussian smearing of the angles and energies of the generated particles was introduced to simulate the effects of detector resolution seen in the data. Interference with the Z^0 changed the cross section for events within the tube chamber acceptance by a maximum of 1.0% from the simple $1/s$ QED dependence. The cross section corresponding to the selection criteria described above was calculated to be 18.17 ± 0.02 nb at the Z^0 peak. A theoretical systematic error of 1% was assigned to this calculation [7]. A 0.14% correction was applied to account for the contribution of the process $e^+e^- \rightarrow \gamma\gamma$. The radiative energy tails in figure 1 agreed well with the predictions of the Monte Carlo program. Throughout the fiducial region the measured average polar angles agreed well with the simulated distribution, which corresponds approximately to $1/\theta^3$, as shown in figure 2.

The sources of error in the absolute luminosity normalisation are detailed in table 1. The dominant contribution is the limited precision in the tube chambers survey, while further errors arise from small discrepancies between the data and the Monte Carlo prediction and residual uncertainties in determining the various correction factors. The final error of 2.2% includes a statistical error of 0.7% corresponding to 17,379 events in the calibration sample.

Table 1: Contributions to the absolute luminosity measurement uncertainty. The systematic errors contributing to the overall uncertainty are listed and then combined with the statistical error.

Source of Error	Magnitude
Theory	1%
Radial survey	1.5%
Efficiency of tube chambers	0.5%
Trigger efficiency	0.3%
Energy cut	0.5%
Radial cut	0.5%
Background subtraction	0.5%
Total systematic error	2.1%
Statistical error	0.7%
Total uncertainty	2.2%

A check was made on the accuracy of the tube chamber luminosity calibration by using the shadow of the beam pipe support ring to establish a well defined inner edge for the calorimeter. This support is a precisely machined aluminium ring with a conical outer surface that points to the interaction region at a polar angle of 47 mrad. It has a thickness of two radiation lengths and is located 40 cm in front of the forward calorimeter. The addition of this material in front of the calorimeter alters the energy sharing between the presampler and the main calorimeter significantly. The energy deposited in the main calorimeter is about 15 GeV lower in the shadow of the beam pipe support ring than beyond it. This discontinuity of the energy distribution in the main calorimeter accurately defines the edge of the acceptance at small θ . A measurement using this method, which is independent of the tube chambers, agreed with the tube chamber

measurement to within $0.8 \pm 2.6\%$.

The relative luminosity between points of different beam energy was measured using the main calorimeters only. Events were selected in which the average energy of the largest clusters seen in the main sections of each calorimeter exceeded 70% of the beam energy. This requirement was high enough to eliminate the background, but was 3 standard deviations below the peak from well contained Bhabha events. It rejected Bhabha events only partially contained due to the radiation of an energetic photon or shower leakage at the edges of the calorimeter. To reduce backgrounds, the difference, $\Delta\phi$, in the azimuthal angles of the largest clusters was required to be in the range $160^\circ < \Delta\phi < 200^\circ$. A total of 58,124 events were selected by these cuts, of which less than 0.1% were background.

The energy calibration of the main calorimeter could be maintained to within 0.5% over the entire period of data taking. As a consequence, the cross section for luminosity events defined by these requirements was stable with time to within 0.8%. With an effective geometrical acceptance extending from 47 to 142 mrad in polar angle, the cross section was affected by Z^0 interference by at most 0.3%. Because the energy cut was imposed on the average of the energies in the two calorimeters, the acceptance was largely independent of beam displacements and the size of the beam intersection region.

The acceptance of the calorimeter selection was normalised to the tube chamber acceptance for a sample which included 70% of the data taking period. The Bhabha cross section for the calorimeter based luminosity measurement was thereby found to be 40.2 ± 0.9 nb at the Z^0 peak. The stability of the measurement was checked by comparing the tube chamber and calorimeter luminosities as a function of LEP fill and beam energy. No statistically significant systematic differences were observed. The beam energy dependent systematic error of the integrated luminosity was estimated to be 1% and was taken into account as a point-to-point systematic error in the cross section measurements.

The data recorded in 1989 correspond to an integrated luminosity of about 1.4pb^{-1} . For the following analysis only those periods of data taking were used in which all detector components essential for the measurement were operating properly.

4 The Hadronic Decays

The selection of hadronic Z^0 decays was mainly based on energy clusters in the electromagnetic calorimeter. Clusters in the barrel region were required to have an energy of at least 100 MeV, and clusters in the end cap were required to contain at least two adjacent lead glass blocks and have an energy of at least 200 MeV. The following three requirements defined a multihadron candidate: (i) at least 8 clusters, (ii) a total energy deposited in the lead glass of at least 10% of the centre-of-mass energy

$$R_{vis} = \Sigma E_{clus} / \sqrt{s} > 0.1,$$

where E_{clus} is the energy of each cluster, and (iii) an energy imbalance along the beam direction which satisfied

$$R_{bal} = | \Sigma (E_{clus} \cdot \cos \theta) | / \Sigma E_{clus} < 0.65.$$

The measured distributions of these variables are shown in figure 3. The cut on the number of clusters efficiently eliminated Z^0 decays into e^+e^- and $\tau^+\tau^-$. The R_{vis} cut discarded two-photon

and beam-gas events. The cut in R_{bal} rejected beam-wall, beam-gas and beam-halo events, and cosmic rays in the end caps.

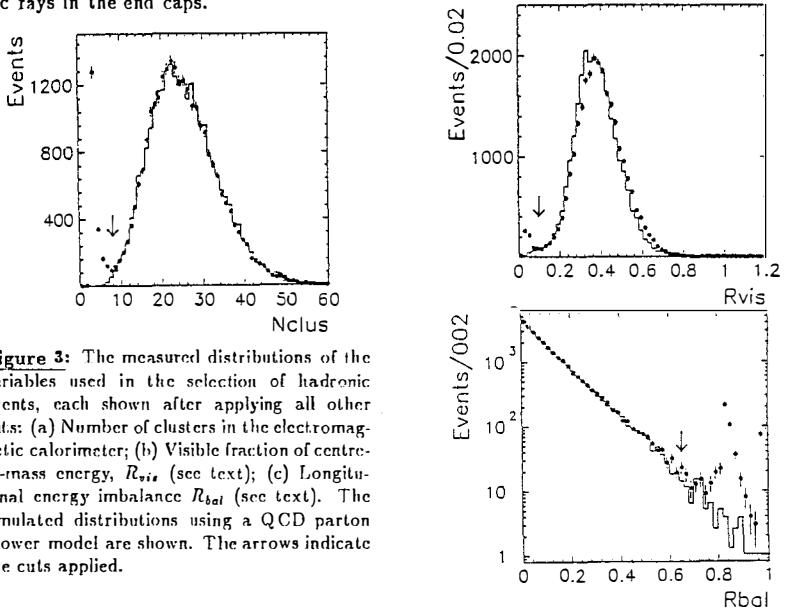


Figure 3: The measured distributions of the variables used in the selection of hadronic events, each shown after applying all other cuts: (a) Number of clusters in the electromagnetic calorimeter; (b) Visible fraction of centre-of-mass energy, R_{vis} (see text); (c) Longitudinal energy imbalance R_{bal} (see text). The simulated distributions using a QCD parton shower model are shown. The arrows indicate the cuts applied.

In order to reject cosmic ray background in the barrel region, information from the TOF counters was used. All events for which at least 4 TOF counters fired within 8 ns of the expected time were accepted. Events with less than 4 TOF counters for which at least 50% of the observed energy was seen in the barrel lead glass were rejected. All remaining events with $N_{TOF} < 4$ were visually inspected. The background from cosmic-rays, beam-wall and beam-halo was estimated to be less than 0.1%. A total of 25,801 hadronic Z^0 decays remained after all these cuts, corresponding to an integrated luminosity of 1.25 pb^{-1} .

The main contamination in the hadronic data sample came from $\tau^+\tau^-$ events with a background fraction of $0.33 \pm 0.04\%$ estimated by using Monte Carlo and checked with the data using the charged track multiplicity. The contribution of the process $e^+e^- \rightarrow e^+e^-$ to the hadronic event sample was found to be less than 0.1%. The background from two-photon processes was estimated by a Monte Carlo calculation using a quark-parton model [8] and was checked with the data by measuring the ratio of the numbers of events with high and low R_{vis} as function of beam energy. Both estimates gave consistent results; the background was $0.03 \pm 0.03\%$ under the Z^0 peak and $0.2 \pm 0.2\%$ in the tail region.

To calculate the acceptance of the event selection procedure, the process $e^+e^- \rightarrow q\bar{q}$ with subsequent hadronisation was simulated using the JETSET parton shower model with five flavours and string fragmentation [9]. There is good agreement between the model predictions and the properties of the hadronic event sample (see for example figure 3 and reference [10]). An acceptance of 97.7% with a negligible statistical error was calculated for multihadronic events. The effect of uncertainties in the fragmentation model was estimated to be 0.5% by varying the parameters of the JETSET model and by using the HERWIG hadronisation model [11]. Imperfections in the detector simulation lead to a variation of the acceptance of 0.5%. The energy dependence of the acceptance in the region of the scan was 0.2%. The error due to the specific

choice of the hadronic selection cuts was estimated to be 0.2%. The resulting total systematic error on the selection and acceptance of hadronic events was 0.8%.

The overall trigger efficiency for hadronic decays of the Z^0 that would pass the acceptance criteria was determined from the redundancy between the three main trigger modes: the TOF trigger, the track trigger and the electromagnetic energy trigger. The overall trigger inefficiency was less than 0.1%.

In table 2 the numbers of events, the integrated luminosities and the corresponding cross sections are listed as a function of the centre-of-mass energy. The error on the cross section includes the statistical errors of the hadronic event sample and of the luminosity as well as a 1% point-to-point systematic error from the luminosity. In the analysis of the cross section an overall normalisation error of 2.3% is taken into account which includes both the systematic error of 2.2% on the luminosity and the systematic error on the acceptance of 0.8%.

Table 2: The hadronic cross section, σ_{had} , as a function of the luminosity-weighted centre-of-mass energy. Listed are also the integrated luminosity and the number of observed hadronic events. The cross sections are quoted with their statistical and point-to-point systematic luminosity error of 1%. The overall systematic error on the cross section is 2.3% and on the energy scale is 30 MeV. The point-to-point error in the energy is 10 MeV.

$\sqrt{s}$ (GeV)	$\mathcal{L}_{int}(\text{nb}^{-1})$	N_{had}	σ_{had} (nb)
88.278	115.1 ± 1.6	569	5.04 ± 0.23
89.283	80.7 ± 1.4	766	9.68 ± 0.40
90.284	103.7 ± 1.6	1990	19.56 ± 0.56
91.034	210.9 ± 2.3	6192	29.94 ± 0.58
91.289	186.2 ± 2.1	5633	30.86 ± 0.62
91.529	230.8 ± 2.4	6612	29.21 ± 0.55
92.282	85.5 ± 1.5	1781	21.24 ± 0.66
92.562	9.2 ± 0.5	150	16.66 ± 1.62
93.286	111.4 ± 1.7	1286	11.77 ± 0.39
94.277	95.4 ± 1.6	710	7.59 ± 0.32
95.036	17.7 ± 0.7	112	6.44 ± 0.66
Total	1246.6	25801	

5 Analysis of the Hadronic Cross Section

To extract the Z^0 resonance parameters from the cross sections given in table 2 and shown in figure 4, we perform a fit to the data assuming the line shape parametrisation of reference [12]. We treat M_z , Γ_z and σ_{had}^{pole} as free parameters where σ_{had}^{pole} represents the peak hadronic cross section at $s = M_z^2$ without photonic corrections. The parameter values obtained are

$$M_z = 91.145 \pm 0.022(exp) \pm 0.030(LEP) \text{ GeV}$$

$$\Gamma_z = 2.526 \pm 0.047 \text{ GeV}$$

$$\sigma_{had}^{pole} = 41.2 \pm 1.1 \text{ nb.}$$

The χ^2 value for this fit is 4.5 for 8 degrees of freedom. The errors on M_z have been separated into the experimental error and the uncertainty due to the LEP beam energy.

Figure 5 shows the central values and the confidence contours for our measurement of Γ_z and σ_{had}^{pole} . Also shown are the Standard Model predictions for σ_{had}^{pole} and Γ_z , for 3 and 4 light

neutrino generations. For the top quark mass m_t and the Higgs mass m_H we assumed $m_t = m_H = 100$ GeV, and we set the strong coupling constant $\alpha_s = 0.12$, consistent with the value derived from the measured hadronic jet production rates [13]. The errors on the predictions are derived by allowing a variation of m_t from 50 to 250 GeV, m_H from 20 to 1000 GeV and α_s from 0.09 to 0.15. Figure 5 shows that the effect of varying the number of light neutrino generations from 3 to 4 is large compared to the uncertainty in the predicted values of σ_{had}^{pole} and Γ_z . The probability for obtaining our measurement assuming three neutrinos is 54% whereas the assumption of four neutrinos would result in a probability of only 0.001%.

Figure 4: Measured multihadron cross sections at the 11 points of the scan. The solid (dashed) curve is the lineshape predicted by the Standard Model assuming the measured M_z for 3 (4) light neutrino generations (see text).

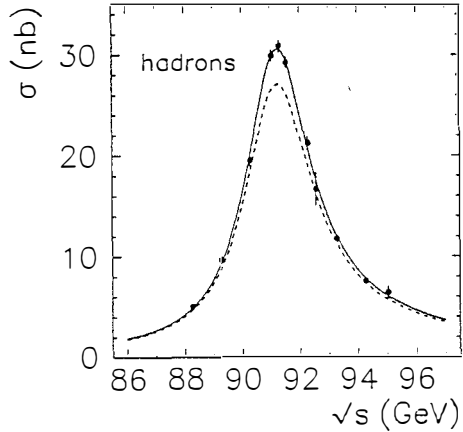
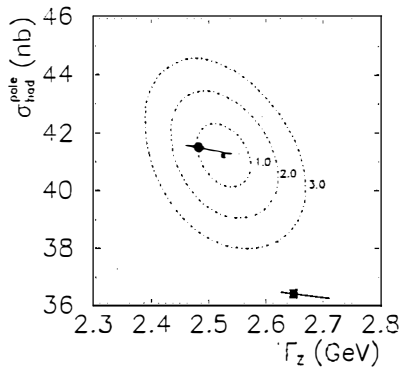


Figure 5: The one, two and three standard deviation confidence contours of our measurement in the $\Gamma_z - \sigma_{had}^{pole}$ plane. The small square shows the best fit to the data; the circle shows the Standard Model prediction for 3 light neutrino generations, the large square the prediction for 4 neutrinos. The bars reflect the uncertainty in the predictions when the top quark mass is varied from 50 to 250 GeV, the Higgs mass from 20 to 1000 GeV and α_s between 0.09 and 0.15.



To determine the number of light neutrinos, N_ν , one can use the Standard Model in a fit where the only free parameters are M_z and N_ν . Though this method is the statistically most precise one, it relies on the validity of the Standard Model prediction for the Z^0 partial widths. We removed this constraint by a combined measurement of the hadronic and the leptonic partial widths [1], which is reported in a separate contribution to this conference [14].

Acknowledgements

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This talk was dedicated to the memory of our colleague Liz Spreadbury.

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