Measurement of the Decay of the Z^0 into Lepton Pairs

The OPAL Collaboration

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(Submitted to Physics Letters)

Abstract

We report on a measurement of the processes $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow \mu^+\mu^-$, and $e^+e^- \rightarrow \tau^+\tau^-$ near the Z^0 pole. On the basis of 163 e^+e^- , 101 $\mu^+\mu^-$ and 87 $\tau^+\tau^-$ events we obtain $\Gamma_{ee} = 89 \pm 4 \pm 4$ MeV, $\Gamma_{\mu\mu} = 85 \pm 9 \pm 6$ MeV and $\Gamma_{\tau\tau} = 87 \pm 10 \pm 8$ MeV, compatible with the standard model. Combining these with our previous results on hadronic Z^0 decays, we find a hadronic width $\Gamma_{\text{had}} = 1787 \pm 81 \pm 90$ MeV and an invisible width $\Gamma_{\text{inv}} = 552 \pm 85 \pm 71$ MeV.

1 Introduction

This paper reports on a determination of the partial widths of the Z^0 boson into charged lepton pairs, that is $Z^0 \rightarrow e^+e^-$, $Z^0 \rightarrow \mu^+\mu^-$, and $Z^0 \rightarrow \tau^+\tau^-$. The data, recorded at the CERN LEP collider during its first 15 days of operation for physics, correspond to an integrated e^+e^- luminosity of about 190 nb^{-1} , and span the energy range from 89.26 to 93.26 GeV. The analysis is restricted to the fiducial region defined by $|\cos\theta| < 0.7$, where θ is the polar angle with respect to the beam direction.

2 The Detector

The OPAL detector [1] has a system of central tracking chambers inside a solenoid that provides a uniform magnetic field of 0.435 T. The solenoidal coil is surrounded by a time-of-flight (TOF) counter array, a lead glass electromagnetic barrel (EB) calorimeter with a presampler, an instrumented magnet return yoke serving as a hadron barrel (HB) calorimeter and four layers of outer muon barrel (MB) chambers. The solid angle coverage of the detector is completed by two endcaps, each also having a lead glass electromagnetic calorimeter with a presampler, a hadron calorimeter and outer muon chambers. We determine the luminosity of the colliding beams by observing small angle Bhabha scattering with the forward detector [2]. This device consists of two identical elements of a lead-scintillator calorimeter placed around the beam pipe at either end of the central detector. It covers angles from 40 to 150 mrad from the beam and 2π in azimuthal angle ϕ . The systematic uncertainty in the determination of the total integrated luminosity is estimated to be 5% [2]. The measurements described here use the central detector, the TOF system, and the barrel part of the electromagnetic calorimeter, the hadron calorimeter and the muon detector. The TOF system and the EB calorimeter cover the region $|\cos\theta| < 0.82$. We discuss briefly those detectors not previously described in [2]. The muon detection system in the barrel region consists of 220 planar drift chambers, each 60 cm wide with a single central wire. They are arranged in 4 layers over a radial distance of about 50 cm. Most of the chambers are 10.4 m long, covering a range in polar angle of $|\cos\theta| < 0.69$. The chambers on top of the detector are 8 m long, to permit cables to reach the detector; in this region the coverage is reduced to $|\cos\theta| < 0.60$. In the space below the detector, where room is taken up by the magnet supports, the chambers are 6 m long and the detector is sensitive only for $|\cos\theta| < 0.47$. The iron structure used for the return field is instrumented as a hadron calorimeter, with 10 cm iron slabs and 9 planes of

limited streamer tubes. The readout of the streamer tubes is arranged in towers and strips. In addition to energy measurement the strip readout permits the identification of minimum ionising particles traversing the iron and thus helps muon identification. The IIB calorimeter covers the range $|\cos\theta| < 0.7$.

3 The Trigger

Triggers sensitive to lepton pair events in the fiducial region $|\cos\theta| < 0.7$ are provided by the barrel lead glass calorimeter, the central detector, the TOF counters, and the muon barrel drift chambers. If any of the following conditions is satisfied the event is recorded:

- i) The energy deposited in the EB calorimeter is larger than 6 GeV (4 GeV if a TOF signal is also present).
- ii) At least two charged tracks are found by the central detector trigger processor.
- iii) Signals are found in two TOF scintillators, back-to-back to within 260 mrad in ϕ .
- iv) A track found in the muon barrel chambers (with three out of four planes) is associated within 260 mrad in ϕ with a signal in a TOF scintillator.
- v) A track found in the muon barrel chambers (with three out of four planes) is associated within 260 mrad in ϕ with a track found in the central detector.

These conditions provide a high degree of redundancy and give almost 100% trigger efficiency for lepton pair detection in the barrel region (see table 1). The selection of e^+e^- , $\mu^+\mu^-$, and $\tau^+\tau^-$ candidates is described for each of the processes separately below.

4 The Selection of $e^+e^- \rightarrow e^+e^-$ Events

The process $e^+e^- \rightarrow e^+e^-$, unlike the other lepton pair channels, has in addition to the s -channel electroweak process a sizable contribution from QED t -channel exchange. In the endcap region the contribution from the Z^0 to this process, even on top of the Z^0 peak, is relatively small, whereas it dominates ($\approx 90\%$) in the barrel region used in this analysis. The trigger efficiency for the $e^+e^- \rightarrow e^+e^-$ process is estimated to be greater than 99.9% in the barrel region. The off-line event selection is mainly based on the information from the barrel lead glass calorimeter. The selection criteria are:

- i) Two clusters are required in the lead glass calorimeter, each with an energy larger than 50% of the beam energy and $|\cos\theta| < 0.7$.
- ii) A total lead glass energy of at least 85% of the centre-of-mass energy is required. This condition eliminates most of the background from $\tau^+\tau^-$ events.
- iii) The acollinearity angle of the two highest energy clusters is required to be less than 87 mrad, allowing hard photon emission only if it is collinear with the final state e^+

or e^- . This cut is applied to allow a comparison with the analytical formula discussed below. The acollinearity distribution is shown in figure 1a, together with the Monte Carlo distribution [3].

A total of 167 events satisfy these conditions. They were all visually scanned. For data with the central detector on (which corresponds to $\approx 85\%$ of the luminosity) it is required that a charged particle is associated with both high energy clusters. Four events are rejected: three are $e^+e^- \rightarrow \gamma\gamma$ and one is $e^+e^- \rightarrow e^+e^-\gamma$ where one of the high energy clusters is a photon. The background contamination in the final event sample is estimated to be less than 1%, arising from $\gamma\gamma$ and $e^+e^-\gamma$ events recorded when the central detector was off and from $\tau^+\tau^-$ events.

The selected numbers of events, the integrated luminosities and the cross sections for $|\cos\theta| < 0.7$ are listed in table 2 for the different energy points. The quoted errors are statistical only. Uncertainties in the energy and angular resolutions of the EB calorimeter contribute a systematic error of 1% to the cross section measurement.

5 The Selection of $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$ Events

The first stage $\mu^+\mu^-$ and $\tau^+\tau^-$ event selections use information from the raw data, analysed on-line in the event filter. Events satisfying any of the following criteria are selected for further analysis:

- i) Energy above 8 GeV is found in the lead glass in coincidence with a TOF signal less than 27 ns after the beam crossing.
- ii) Two lead glass clusters above 100 MeV are found, back to back in θ (± 160 mrad) and ϕ (± 200 mrad), and each associated with an in-time TOF signal.
- iii) Two lead glass clusters above 100 MeV are found, back to back as above, at least one of which is associated with an in-time TOF signal and a muon track to within 150 mrad in ϕ .
- iv) A lead glass cluster above 100 MeV, an in-time TOF signal, and a muon track are found within 87 mrad in ϕ .
- v) Two central detector tracks are found, and at least one in-time TOF signal associated to a lead glass cluster to within 80 mrad.
- vi) Trigger (iv) or (v) is satisfied, and at least one central detector track is found.

Filter efficiencies are given in table 1 for both channels.

We perform the search for $\mu^+\mu^-$ and $\tau^+\tau^-$ events using only those data for which the central detector was at nominal operating voltage and its track trigger was operational. In addition, events are removed as multihadrons if they have more than 10 charged tracks or more than 12 lead glass clusters with energy above 250 MeV. Here, a charged track is defined as a track with at least 30 of a possible 159 hits in the central detector, the first of which is at

a radius of less than 75 cm, satisfying the following criteria: $p_T > 100$ MeV and $d_0 < 3$ cm. p_T is the momentum of the track in the plane perpendicular to the electron-positron beam direction and d_0 is the distance of closest approach to the nominal interaction point in this plane.

For the detection of $\mu^+\mu^-$ events, the triggers described above provide a high degree of redundancy. This allows us to estimate the trigger efficiencies from the data. The efficiency of the central detector trigger is found to be 95% per track, from the number of tracks found in events that satisfied other triggers. In the trigger and the event filter signals from both ends of a TOF scintillator are required. We find the TOF efficiency to be 80% per track by using events satisfying the track and muon triggers, and the muon trigger efficiency to be 90% per muon. The efficiencies for the three components are assumed to be independent. The separate efficiencies for the two muons in the event are also assumed to be independent, except for 5% of the solid angle where the inefficiencies are correlated due to the short MB chambers on the top and bottom of the experiment. Then the combined efficiency from the triggers (ii) to (v) above, is $99 \pm 1\%$. These efficiencies, and their independence, are confirmed by a study of the 15 possible observable combinations of these 4 triggers, in which the predictions agree well with the observed frequencies of occurrence. Similarly, the filter conditions (ii) to (vi) described above give a high degree of redundancy for the selection of $\mu^+\mu^-$ events. The same type of study gives an overall filter efficiency of $95 \pm 2\%$.

A $\mu^+\mu^-$ candidate must have at least two charged tracks identified as muons by any one of the following three detectors: muon chambers, hadron calorimeter strips or electromagnetic calorimeter. Both tracks in the central detector must have at least 30 hits, the first of which is at a radius of less than 75 cm, and must satisfy $p_T > 2$ GeV, $|\cos\theta| < 0.7$, and $d_0 < 1$ cm. The angle between the two tracks in ϕ must be greater than 250 mrad. A track is identified as a muon if it satisfies any one of the following criteria:

- i) There are at least two MB hits within $\Delta\phi = 6.3$ mrad of the track.
- ii) Within $\Delta\phi = 6.3$ mrad there is a track with hits in at least five of the nine layers in the HB.
- iii) The sum of the energies in EB of all clusters within $\Delta\phi = 250$ mrad is less than 3 GeV and the momentum of the track is greater than 20 GeV.

The measured efficiencies of the above three conditions are: 95.6% (MB), 68.1% (HB) and 90.6% (EB). The HB efficiency is less than nominally expected because of technical startup problems. The combined efficiency for correctly identifying both tracks as muons is 99.8%.

TOF information is used to remove the remaining background from cosmic rays. Off-line, TOF hits can be used even if only one end of the scintillator gives a signal. For events in which TOF information is obtained for both tracks, the time difference between the two TOF counters is shown in figure 1b. Events for which this difference is larger than 12 ns are rejected as cosmic ray muons. For all TOF hits in the events passing this cut the difference between the expected and the measured flight time, Δt , is shown as the open histogram in figure 1c. The shaded histogram in this figure represents the Δt from the 12 events in which only one TOF counter fires; these events are accepted if $|\Delta t| < 10$ ns. Events in which no TOF counter fires are rejected. The TOF requirements introduce an efficiency of 99.8%. The

combined off-line selection efficiency is $99 \pm 1\%$ within $|\cos\theta| < 0.7$. With these cuts 101 events are finally selected as muon pairs.

A number of checks of the analysis has been performed. A second selection technique was used, in which only one track was required. The results of this analysis are in agreement with the first method. All selected events have been scanned, and no obvious background events were found. In addition, for a period corresponding to half of the accumulated luminosity, we have scanned events satisfying much looser criteria, and found no extra $\mu^+\mu^-$ events. We have also used the e^+e^- sample described earlier to confirm the calculations of the central detector trigger efficiency, and to check the charged track selection criteria.

From the TOF information, we determine the number of cosmic ray events in our sample to be less than one. Since we make no stringent cut on the momenta of the tracks our sample includes tau pairs where both tau leptons decay to a muon, of which we expect roughly 3. In addition there is some tau pair background due to a tau decay to a pion which then fakes a muon. A Monte Carlo calculation gives a total of 4.1 ± 1.9 background events from $Z^0 \rightarrow \tau^+\tau^-$. From a Monte Carlo simulation [4] of $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ we calculate a background of 1.0 ± 0.1 events. Figure 1d shows the acoplanarity distribution of the data together with Monte Carlo predictions for the $e^+e^- \rightarrow \tau^+\tau^-$ and $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ background (shaded histogram) and for muon pairs plus background (open histogram). It can be seen that the contamination is small.

We have evaluated the acceptance of the requirement that both tracks are within $|\cos\theta| < 0.7$ to be $59.4 \pm 1.6\%$, using $\mu^+\mu^-$ events generated with the KORALZ Monte Carlo [5]. This Monte Carlo generates $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$ according to the standard model, including the effects from initial and final state radiation. The generated events are processed by the GOPAL [6] program, a simulation of the OPAL detector, based on the GEANT [6] code for particle tracking through materials. The GOPAL program includes effects of detector resolution and efficiencies and produces output identical in format to that of the OPAL data acquisition system, such that it can be processed by the same analysis chain as the real events.

Taking into account the efficiency, acceptance and background as summarised in table 1, we calculate a corrected number of $N_{\mu\mu} = 173 \pm 18 \pm 7$ μ -pair Z^0 decays in the sample, where the first error is statistical and the second systematic. The systematic error is dominated by the uncertainty in the acceptance and the background subtraction. In the same data sample we find $N_{\text{had}} = 3701 \pm 62 \pm 38$ hadronic decays. Thus the ratio of muon to hadron decays of the Z^0 is $N_{\mu\mu}/N_{\text{had}} = 4.7 \pm 0.5 \pm 0.2 \%$.

In the selection of τ -pair candidates, events are required to have fired the total EB energy trigger (i). Using independent triggers, we find the efficiency of this trigger for the $\tau^+\tau^-$ events passing the final off-line selection to be greater than 99%. Tau-pair candidates are required to pass filter criterion (i). The efficiency of this criterion for events satisfying the final selection is determined with the two independent filter criteria (ii) and (iii), and found to be $99 \pm 1\%$. The final $\tau^+\tau^-$ sample is selected with the following criteria:

- i) The total electromagnetic energy reconstructed in the lead glass must be larger than 12 GeV to reject muon pairs and to ensure good trigger and filter efficiency, and less than 70 GeV to reject electron pairs.

- ii) The thrust axis is calculated from the electromagnetic clusters and the charged tracks in the central detector. Only events for which $|\cos\theta_T| < 0.7$ are kept, where θ_T is the angle between the thrust axis and the beam axis. This cut ensures good acceptance for the lead glass barrel, the central detector and the TOF counters.
- iii) The plane perpendicular to the thrust axis divides the event in two hemispheres. In each hemisphere the number of reconstructed charged tracks must be greater than zero and less than five. Here, a charged track is defined by the rather loose cuts: $d_0 < 3$ cm, $p_T > 100$ MeV, more than 30 hits in the central detector and radial position of the first measured point less than 75 cm.
- iv) Muon-pair events, identified as such by the muon selection described above, are rejected. Five events are removed from the final sample by this cut.
- v) As in the muon-pair analysis, events with back-to-back TOF hits are rejected if the time difference is greater than 12 ns.
- vi) Backgrounds from two-photon exchange reactions and beam-gas events are rejected by the requirement of a minimum angle of 80 mrad between the beam axis and the sum of the energy vectors measured in the lead glass.

A total of 87 events satisfy these criteria. All the selected events and a fraction of the rejected events were visually scanned to check the selection program. No obvious background was found.

We estimate the contribution from various background processes by subjecting samples of simulated background events to our selection program. The considered background channels are: $e^+e^- \rightarrow \text{hadrons}$ (3.4 ± 1.6 events), $e^+e^- \rightarrow e^+e^-$ (1 ± 1 event), $e^+e^- \rightarrow \mu^+\mu^-\gamma$ (0.3 ± 0.3 events) and $e^+e^- \rightarrow e^+e^-X$ (0.6 ± 0.3 events). We estimated the background from cosmic rays (1 ± 1 events) by relaxing the cut on d_0 to 6 cm; only one additional event passed our criteria. In total, the background in our final sample is estimated to be 6.3 ± 2.2 events.

The distributions relevant to the most critical cuts, (i) and (iii), are shown in figure 2. In figure 2a, the energy distribution is shown for events passing all cuts except (i), the total energy cut. Plotted is the measured energy as a fraction of the e^+e^- centre-of-mass energy. The e^+e^- peak and the minimum ionising energy peak of $\mu^+\mu^-$ events are clearly visible. In between lie the $\tau^+\tau^-$ events, as is seen from the shaded distribution from the KORALZ Monte Carlo. There is good agreement between the Monte Carlo and the data. Above 0.1, the ratio of data to Monte Carlo events is insensitive to the lower energy cut to within 2.6%. This cut is the main contribution to the inefficiency within the fiducial acceptance: it removes 20.5% of the events with $|\cos\theta| < 0.7$. The effect of the multiplicity cut (iii) can be seen in figure 2b, where the charged multiplicity in one hemisphere is plotted if the other hemisphere has one or more charged tracks. The ratio of one-prong to three-prong decays is reasonably well simulated, the zero-, two- and four prong bins are strongly depleted. The discrepancy in the first bin arises from backgrounds, mainly cosmic ray events with badly measured tracks. After background subtraction, a small excess remains in the two- and four-prong bins. This excess is due either to an uncertainty in the central detector simulation, or to an underestimate of the background. We assign a systematic error of 4.4% due to this effect. We estimate the

overall systematic error in the acceptance by combining the uncertainties due to the cuts. To the 4.4% error of the multiplicity cut and the 2.6% of the energy cut, we add 2.2% and 3.0% for cuts (ii) and (vi), respectively, and 3% for Monte Carlo statistics to obtain an overall relative systematic error on the acceptance of 7.0%.

We determine the selection and reconstruction efficiency with a Monte Carlo simulation. Events are generated with the KORALZ Monte Carlo [5] in which all relevant decay modes of the tau lepton are simulated. By applying the same cuts to the Monte Carlo as to the data, we obtain a reconstruction efficiency of $73 \pm 4.3\%$ for events within $|\cos\theta| < 0.7$, and a geometrical acceptance of $63.6 \pm 2.4\%$.

Taking into account the efficiencies, acceptance and background as summarised in table 1, we find the corrected number of τ -pair Z^0 decays in the sample to be $N_{\tau\tau} = 175 \pm 20 \pm 13$. The ratio of tau to hadron decays of the Z^0 is therefore $N_{\tau\tau}/N_{\text{had}} = 4.7 \pm 0.6 \pm 0.4 \%$.

6 Results

In figure 3, we show the cross sections for all three processes as a function of the centre-of-mass energy around the Z^0 pole. In the following paragraphs, we use these cross sections to determine the partial decay widths.

In order to obtain the partial decay width Γ_{ee} the analytical formula for the $e^+e^- \rightarrow e^+e^-$ process is used [7], which includes the Breit-Wigner form for the Z^0 with an s -dependent width, QED s - and t -channel contributions and radiative corrections (all one-loop diagrams and soft and collinear photon effects). After applying the same cuts on energy, polar angle and acollinearity as for the data, we compare the calculated with the measured cross sections. The influence of the top mass on the line shape is negligible and its value was fixed at 100 GeV. We performed a fit for Γ_{ee} by varying the effective $\sin^2\theta_W$ [7]. M_Z and Γ_Z are fixed to the values determined previously using the $Z^0 \rightarrow \text{hadrons}$ channel [2]: $M_Z = 91.01 \pm 0.05 \pm 0.05$ GeV and $\Gamma_Z = 2.60 \pm 0.13$ GeV. The result is $\Gamma_{ee} = 89 \pm 4 \pm 4$ MeV. The systematic error comes mainly from the overall normalisation error on the luminosity ($\pm 5\%$) and from the error on the total width measurement [2]. The result of the fit is shown as the solid line in figure 3a. The dashed line in figure 3a represents the standard model prediction [8] with three generations and the Z^0 mass given above.

The numbers of measured $\mu^+\mu^-$ and $\tau^+\tau^-$ events and the cross sections as a function of energy are summarised in table 3. To obtain a model independent parametrisation of our data we use a Breit-Wigner lineshape with s -dependent width, convoluted with an initial state radiation function as described in [2]. In this analysis, we set the Z^0 mass and width to be our measured values [2]. The formula is an approximation since it does not correctly treat the s -channel contribution from QED. This approximation holds well for hadrons. For $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$ the error introduced on the determination of the pole cross section is estimated to be less than 1.5%. The pole cross sections, determined by a maximum likelihood fit, are found to be $\sigma_{\mu\mu}^{\text{pole}} = 1.99 \pm 0.19 \pm 0.14$ nb and $\sigma_{\tau\tau}^{\text{pole}} = 2.02 \pm 0.21 \pm 0.19$ nb. The results of these fits are the solid curves in figures 3b and 3c, and are compared to the standard model expectations, shown by the dashed curves.

To test lepton universality we determine the ratio of the muon to electron partial decay widths using the relation

$$\sigma_{\mu\mu}^{\text{pole}} = \frac{12\pi}{M_Z^2} \frac{\Gamma_{ee}\Gamma_{\mu\mu}}{\Gamma_Z^2}, \quad (1)$$

and similarly for $\sigma_{\tau\tau}^{\text{pole}}$. Using our measured values for $\sigma_{\mu\mu}^{\text{pole}}$, $\sigma_{\tau\tau}^{\text{pole}}$, M_Z , Γ_{ee} , and Γ_Z , we find

$$\frac{\Gamma_{\mu\mu}}{\Gamma_{ee}} = 0.96 \pm 0.12 \pm 0.05, \text{ and } \frac{\Gamma_{\tau\tau}}{\Gamma_{ee}} = 0.97 \pm 0.13 \pm 0.08.$$

The ratio of muon to tau partial decay widths, simply defined by the ratio of the number of decays in each channel, is $N_{\mu\mu}/N_{\tau\tau} = 0.99 \pm 0.15 \pm 0.08$. Each of these ratios is consistent with unity and hence consistent with lepton universality. Our measurements of the individual partial widths are summarised in table 4. The values are consistent with previous measurements [9] and the standard model expectation of 82.9 MeV. The hadronic decay width Γ_{had} can be calculated in the same way, by using $\sigma_{\text{had}}^{\text{pole}}$ and Γ_Z from [2]. The branching ratios in table 4 are determined by the ratios of the decay widths to the total Z^0 decay width.

If we assume lepton universality, we can determine the partial lepton decay width from the $\mu^+\mu^-$ data sample with equation (1), by replacing Γ_{ee} and $\Gamma_{\mu\mu}$ by Γ_{l+l-} . This is also done for the $\tau^+\tau^-$ data sample and along with our measurement of Γ_{ee} , the combined result is $\Gamma_{l+l-} = 88.1 \pm 4.6$ MeV, where the error includes the statistical and systematic errors.

With our measurements of hadronic and leptonic Z^0 decays, the partial decay width of the Z^0 into invisible final states can be determined in a model independent fashion. The invisible width, written in terms of our measured quantities, is

$$\begin{aligned} \Gamma_{\text{inv}} &= \Gamma_Z - \Gamma_{\text{had}} - \Gamma_{ee} - \Gamma_{\mu\mu} - \Gamma_{\tau\tau} \\ &= \Gamma_Z - \frac{M_Z^2}{12\pi} (\sigma_{\text{had}}^{\text{pole}} + \sigma_{\mu\mu}^{\text{pole}} + \sigma_{\tau\tau}^{\text{pole}}) \frac{\Gamma_Z^2}{\Gamma_{ee}} - \Gamma_{ee}. \end{aligned}$$

With the above values, we find $\Gamma_{\text{inv}} = 552 \pm 85 \pm 71$ MeV. This corresponds to 3.3 ± 0.7 neutrino generations, each contributing the standard model partial width of 165 MeV.

7 Summary

In summary, we measure the partial decay widths of the Z^0 into e^+e^- , $\mu^+\mu^-$, and $\tau^+\tau^-$. Our results are consistent with lepton universality and we find the partial leptonic decay width to be $\Gamma_{l+l-} = 88.1 \pm 4.6$ MeV. We determine the invisible width of the Z^0 to be $\Gamma_{\text{inv}} = 552 \pm 85 \pm 71$ MeV.

8 Acknowledgements

It is a pleasure to thank the LEP Division for the remarkably smooth running of the machine and their continuing close cooperation with our experimental group. In addition to the support staff at our own institutions we are pleased to acknowledge the following: The

Bundesministerium für Forschung und Technologie, FRG, The Department of Energy, USA, The Institut de Recherche Fondamentale du Commissariat à l'Energie Atomique, The Israeli Ministry of Science, The Minerva Gesellschaft, The National Science Foundation, USA, The Natural Sciences and Engineering Research Council, Canada, The Japanese Ministry of Education, Science and Culture (the Monbusho) and a grant under the Monbusho International Science Research Program, The Science and Engineering Research Council, UK and The A. P. Sloan Foundation.

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Channel	Trigger (%)	Filter On-line (%)	Selection Off-line (%)	Background (%)	Geometrical Acceptance (%)	Global Efficiency (%)
e^+e^-	> 99.9	not used	> 99.0	1.0	---	---
$\mu^+\mu^-$	99.0 ± 1.0	95.0 ± 2.0	99.0 ± 1.0	5.0 ± 2.0	59.4 ± 1.6	55.3 ± 2.0
$\tau^+\tau^-$	> 99.0	99.0 ± 1.0	73.0 ± 4.3	7.2 ± 2.5	63.6 ± 2.4	46.0 ± 3.3

Table 1: Summary of efficiencies for the leptonic channels. The first three columns give the percentage efficiencies in the $|\cos\theta| < 0.7$ region of the trigger, the on-line filter and the off-line selection cuts. The fourth column gives the percentage background in the selected samples. The fifth and the last columns give the geometrical acceptance of the barrel ($|\cos\theta| < 0.7$) and the global efficiency.

$\sqrt{s}$ (GeV)	L_{int} (nb $^{-1}$)	$N_{e^+e^-}^{\text{obs}}$	$\sigma_{e^+e^-}$ (nb) $ \cos\theta < 0.7$
89.26	15.37 ± 0.52	8	0.52 ± 0.19
90.26	26.51 ± 0.69	25	0.94 ± 0.19
91.02	22.90 ± 0.65	33	1.44 ± 0.25
91.26	72.43 ± 1.15	81	1.12 ± 0.13
92.26	12.51 ± 0.49	6	0.48 ± 0.20
92.51	10.73 ± 0.45	2	0.19 ± 0.13
93.26	29.90 ± 0.76	8	0.27 ± 0.10

Table 2: The centre-of-mass energies $\sqrt{s}$, the integrated luminosities L_{int} , event counts $N_{e^+e^-}^{\text{obs}}$ and the cross sections $\sigma_{e^+e^-}$. The quoted errors are statistical only.

$\sqrt{s}$ (GeV)	L_{int} (nb $^{-1}$)	$N_{\mu^+\mu^-}^{\text{obs}}$	$\sigma_{\mu^+\mu^-}$ (nb)	$N_{\tau^+\tau^-}^{\text{obs}}$	$\sigma_{\tau^+\tau^-}$ (nb)
89.26	14.02 ± 0.47	3	0.37 ± 0.21	6	0.87 ± 0.35
90.26	19.50 ± 0.58	17	1.50 ± 0.36	11	1.14 ± 0.34
91.02	14.01 ± 0.43	14	1.71 ± 0.46	9	1.30 ± 0.43
91.26	62.31 ± 1.00	44	1.21 ± 0.18	47	1.53 ± 0.22
92.26	12.08 ± 0.47	8	1.14 ± 0.40	7	1.17 ± 0.44
92.51	8.16 ± 0.36	1	0.21 ± 0.21	3	0.74 ± 0.43
93.26	29.47 ± 0.74	14	0.82 ± 0.22	4	0.27 ± 0.14

Table 3: The centre-of-mass energies $\sqrt{s}$, the integrated luminosities L_{int} , event counts $N_{\mu^+\mu^-}^{\text{obs}}$ and $N_{\tau^+\tau^-}^{\text{obs}}$ and the cross sections $\sigma_{\mu^+\mu^-}$ and $\sigma_{\tau^+\tau^-}$. The quoted errors are statistical only.

X	Γ_X (MeV)	$B(Z^0 \rightarrow X)$ (%)
e^+e^-	$89 \pm 4 \pm 4$	$3.42 \pm 0.15 \pm 0.11$
$\mu^+\mu^-$	$85 \pm 9 \pm 6$	$3.28 \pm 0.34 \pm 0.17$
$\tau^+\tau^-$	$87 \pm 10 \pm 8$	$3.33 \pm 0.37 \pm 0.26$
hadrons	$1787 \pm 81 \pm 90$	$68.7 \pm 3.1 \pm 2.0$
invisible	$552 \pm 85 \pm 71$	$21.2 \pm 3.3 \pm 2.3$

Table 4: Summary of the Z^0 decay widths and branching ratios. The first error is statistical, the second systematic. The errors are correlated.

Figure 1: a) The acollinearity distribution for the e^+e^- events (points with error bars) compared with a prediction from the BABAMC [3] Monte Carlo including the simulation of detector resolution. b) Time difference of back-to-back TOF signals for $\mu^+\mu^-$ events passing all but the TOF requirements. c) Open histogram: the difference between expected and measured time of flight for all TOF hits in events passing the $t_1 - t_2 < 12$ ns cut in figure 1b. Shaded histogram: the time difference for events containing only one TOF hit. d) The acoplanarity distribution for the $\mu^+\mu^-$ data. The shaded histogram is a Monte Carlo simulation of the background from $e^+e^- \rightarrow \tau^+\tau^-$ and $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ events. The open histogram is a Monte Carlo simulation of $e^+e^- \rightarrow \mu^+\mu^-$ events plus the background. The arrows in a), b) and c) indicate where cuts are applied in the event selection.

Figure 2: a) The fraction of the centre-of-mass energy observed in the lead glass calorimeter for preselected $\tau^+\tau^-$ events before the total energy cut. The shaded histogram is the energy fraction obtained by Monte Carlo for $\tau^+\tau^-$ events. b) The multiplicity distribution for preselected $\tau^+\tau^-$ events before the multiplicity cut. Plotted is the number of tracks in a hemisphere opposite a hemisphere with at least one track. Events with tracks in both hemispheres have two entries. The histogram represents the same distribution for the Monte Carlo events.

Figure 3: a) Total cross section for $e^+e^- \rightarrow e^+e^-$ integrated over $|\cos\theta| < 0.7$. b) and c) Total cross sections for $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$, respectively. The errors are statistical only. The solid lines are fits to the Z^0 lineshape, using $M_Z = 91.01 \pm 0.07$ GeV and $\Gamma_Z = 2.6 \pm 0.13$ GeV. The dashed lines represent the standard model prediction with $M_Z = 91.01$ GeV.

Fig. 1

Fig. 2

Fig. 3