A measurement of the Z0 leptonic partial widths and the vector and axial vector coupling constants
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A MEASUREMENT OF THE Z° LEPTONIC PARTIAL WIDTHS
AND THE VECTOR AND AXIAL VECTOR COUPLING CONSTANTS

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We have measured the partial widths of the $Z^0$ into lepton pairs, and the forward–backward charge asymmetry for the process $e^+e^- \rightarrow g^+g^-$ using the L3 detector at LEP. We obtain an average $\Gamma_{e\mu}$ of $83.0 \pm 2.1 \pm 1.1$ MeV. From this result and the asymmetry measurement, we extract the values of the vector and axial vector couplings of the $Z^0$ to leptons: $g_v = -0.066 \pm 0.027$ and $g_A = -0.495 \pm 0.007$.

1. Introduction

The mass and width of the $Z^0$ have been accurately determined at LEP [1,2], using data from the reaction $e^+e^- \rightarrow$ hadrons. Precise measurements of $\Gamma_{e\mu}$, the partial width of the $Z^0$ into charged leptons, and of the lepton charge asymmetries can be used to determine parameters within the standard model [3] and to test the validity of that model. In this paper we present our determination of $\Gamma_{e\mu}$ and of the $Z^0$ to leptons: $g_v = -0.066 \pm 0.027$ and $g_A = -0.495 \pm 0.007$.

2. Data collection

The L3 detector has been described in detail elsewhere [5]. It consists of a central tracking and vertex chamber, a BGO electromagnetic calorimeter, a had-
ron calorimeter made of uranium, brass and proportional wire chambers and a high precision muon chamber system. The calorimeter system covers 99% of 4π. Luminosity is measured by detecting small angle Bhabha events in two forward BGO calorimeters.

The $e^+e^-$ data sample used in this analysis was obtained during October–December 1989 at LEP. The luminosity corresponding to this data sample was measured with a systematic error of 1.7%, as described in detail in ref. [1]. The $\mu^+\mu^-$ sample includes data from the same period plus data from September where the luminosity systematic error is 4%.

Events of the type $e^+e^-\rightarrow e^+e^- (\gamma)$ were detected in the BGO barrel calorimeter. They were triggered using an “energy trigger” with a total energy requirement of 12 GeV, as well as clustered energy triggers [6]. The trigger efficiency has been studied using $e^+e^-\rightarrow e^+e^- (\gamma)$ events selected by the off line analysis. From the comparison of trigger data with the signals from the BGO readout, both of which were digitized and recorded on tape, dead trigger channels have been located and the efficiency measured. The totally efficiency is determined to be $0.975 \pm 0.014$ (stat) for the whole running period.

The principal trigger for $e^+e^-\rightarrow \mu^+\mu^- (\gamma)$ events requires two or more tracks in the muon chambers and at least two hits in the plastic scintillators surrounding the BGO calorimeter. The scintillator trigger efficiency has been studied using a second, looser trigger, which requires at least one track in the muon chambers and at least one scintillator hit. The efficiency of the muon track trigger was measured by analyzing inclusive muon events that are triggered by the energy trigger as well as the muon trigger. From these studies we determine an efficiency greater than 99.5% for the di-muon trigger.

3. Event selection

Events from the process $e^+e^-\rightarrow e^+e^- (\gamma)$ in the angular region covered by the BGO electromagnetic calorimeter ($42^\circ$–$138^\circ$) were extracted from the data by requiring that the total energy measured in the BGO be above $0.72\sqrt{s}$. At least 2 clusters in the BGO, with energies between 10 and 55 GeV were required, and the two highest energy clusters were required to have an acollinearity angle between them of less than 90°.

The efficiency for selecting $e^+e^-\rightarrow e^+e^- (\gamma)$ events which enter the BGO angular region was obtained by Monte Carlo calculation [7]. The detector simulation took account of the small number of inactive channels in the BGO calorimeter for each running period. We found an efficiency of $0.961 \pm 0.010$ for events within the defined angular region for the cuts described above.

For the same cuts, the background from $\tau\tau$ and $e^+e^-\rightarrow$ hadrons was found to be less than 0.3% of the final $e^+e^-$ event sample. The background due to $e^+e^-\rightarrow \gamma\gamma$ has been calculated according to ref. [8], and has been subtracted from the data at each value of $\sqrt{s}$. For $\sqrt{s}=M_{\gamma\gamma}$, this background amounted to 1.8% of the signal cross section. The contribution of the “two photon process” $e^+e^-\rightarrow e^+e^- e^+e^-$ to the final sample was calculated to be negligible.

Adding in quadrature the systematic errors in the trigger efficiency (1.4%), the acceptance (1.0%), the event selection (0.5%), the background subtractions (0.2%) and the luminosity measurement (1.7%), we obtain a total systematic error of 2.5% in the $e^+e^-\rightarrow e^+e^- (\gamma)$ cross section.

Events from the process $e^+e^-\rightarrow \mu^+\mu^- (\gamma)$ were selected by requiring:

1) two tracks in the muon chambers with a reconstructed momentum greater than 2 GeV, with at least one track pointing to within 200 mm of the vertex,
2) total energy deposited in the hadron calorimeter less than 15 GeV,
3) less than 15 shower peaks in the electromagnetic calorimeter,
4) acollinearity angle between the two muons less than 15°.

In order to include final state radiation we define $E_{\mu}$ as the muon momentum plus the energy contained in a cone of semi-aperture 15° around the muon trajectory in the BGO calorimeter. We required:

5) $0.30\sqrt{s}<E_{\mu}<0.70\sqrt{s}$, for muons measured in all three muon chamber planes. The sum of the two $E_{\mu}$ was required to be above 40 GeV.

Each muon track had to have a scintillator hit. Using the scintillator timing, corrected for the flight path from the interaction region to the scintillator, we required at least one of the following:

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(6a) the times for both muons had to be within 
\pm 2.5 \text{ ns} \text{ of the beam crossing time and their differ-}
\text{ence less than 2.5 ns, or}

(6b) the time for one of the muons had to be within 
2.5 \text{ ns} \text{ of the beam crossing, and both muons had to}
satisfy a tight vertex cut.

Cuts (2) and (3) were used mainly to reject had-
ron events with muon pairs while cuts (4) and (5)
removed events of the type \(e^+e^-\rightarrow e^+e^-\mu^+\mu^-\) and 
\(e^+e^-\rightarrow \tau^+\tau^-\rightarrow \mu^+\mu^-+\nu's\). Cut (6) was applied to 
reject cosmic ray background, without losing those 
\(e^+e^-\rightarrow \mu^+\mu^-\) events where one scintillator was hit out 
of time due to a random coincidence with back-
ground in the scintillator.

From the analysis of simulations for the process 
\(e^+e^-\rightarrow x+x^--\rightarrow t+g^-+\nu's\) \[9\], we estimate a con-
tamination of \((0.7 \pm 0.3)\%\) in the selected muon pair 
sample. The other background sources mentioned
above (cosmic rays, \(\mu^+\mu^-\) from the two photon pro-
cess) have been found to give negligible contributions.

The acceptance for \(e^+e^-\rightarrow \mu^+\mu^- (\gamma)\) was calcu-
lated by applying the same cuts on events generated 
by a Monte Carlo program \[9\] and simulated in the 
L3 detector. We found an overall acceptance of 
\(0.505 \pm 0.009\) \text{ (Monte Carlo statistical error)\). A cor-
rection varying in time during the running period has 
been applied to the acceptance, in order to account 
for slight changes in the detector performance. The 
sources of systematic error are then: 2.1\% due to lu-
minozity measurement, 1.8\% due to Monte Carlo 
statistics, 0.4\% due to event selection, and 0.5\% due 
to trigger efficiency. Combining the systematic errors 
in quadrature we obtain a total systematic error in 
the \(e^+e^-\rightarrow \mu^+\mu^-\) cross section of 2.8\%.

4. Partial width for \(Z^0\rightarrow e^+e^-\)

Because of the lack of a sufficiently accurate Monte 
Carlo generator for the \(e^+e^-\) channel, the error on 
the theoretical cross section corresponding to our 
event sample, and hence on our determination of \(\Gamma_{ee}\)
could be significant. We have therefore used two 
methods to determine \(\Gamma_{ee}\) from our electron data. In 
the first and most direct method, we subtracted the 
contribution of the \(t\) channel \(\gamma\) exchange term and its 
interference from the three data points around the 
peak. For these points, the subtraction is only a 
\((16 \pm 1.6)\%\) correction to the data.

In the second method a fit using an analytical for-
formula given in ref. \[10\] was used. This has the advan-
tage of using all of the data whether on or off the peak, 
but may be systematically less accurate because only 
simple cuts are available in the calculation. Results 
from both methods are presented below, and are in 
agreement within the theoretical systematic errors 
quoted. We consider the value obtained using method 
1 as our basic result on \(\Gamma_{ee}\), and we have used it in the 
analysis in the following sections of this paper.

For the first method, the cross sections measured 
in the \(42^\circ -138^\circ\) polar angle range are given in table 
1. The errors shown are statistical only. The back-
ground from \(e^+e^-\rightarrow \gamma\gamma\) has been subtracted in these 
cross sections. To make the \(t\)-channel subtraction, we 
obtained the cross sections into di-electrons and into 
di-muons, \(\sigma_{MC}^{ee}\) and \(\sigma_{MC}^{\mu\mu}\), from Monte Carlo sim-
ulations \[7,9\] and we calculated the \(s\)-channel con-
tribution to the cross section as

\[
\sigma_{Z^0} = \sigma_{\text{exp}} - (\sigma_{MC}^{ee} - \sigma_{MC}^{\mu\mu}) \\
\]

We then find
\[
\Gamma_{ee} = 81.1 \pm 2.8 \text{ (stat)} \pm 1.2 \text{ (syst)} \\
\pm 0.7 \text{ (theory) MeV} \\
\]

The statistical error quoted above includes a con-
tribution of 1.6 MeV from the statistical error on the 
measured total width of the \(Z^0\), as determined from 
our hadron data \(\Gamma_Z = 2.539 \pm 0.054 \text{ GeV}, M_Z = 91.160 \pm 0.038 \text{ GeV} \[1\] \).

In the second method we fitted the cross section as 
a function of \(\sqrt{s}\) using the analytic expression \[10\] 
mentioned above, which takes into account both the 
\(\gamma\) and the \(Z^0\) exchange diagrams in the \(s\) and \(t\) chan-
nels with interference terms. Soft radiation is ac-
counted for by exponentiation, and hard photons are 
included in the collinear approximation. Further cuts 
had to be applied to the data in order to reject events 
containing hard photons (of energy \(k > k_{\text{max}}\)) emit-
ted at large angles \((\delta > \delta_{\text{max}})\) with respect to the direc-
tion of the electrons (or positrons), since these events 
are not accounted for by the fitting function. Events 
with hard acollinear photons in the beam pipe are re-
jected by an acollinearity cut \(A_{\text{max}}\) on the final state 
\(e^+e^-\). Choosing \(A_{\text{max}}\) effectively sets the \(k_{\text{max}}\) used.
Table 1
The number of events and the measured cross sections for $e^+e^-\rightarrow e^+e^-$, for the selection criteria used in methods 1 and 2 described above.

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>Method 1</th>
<th>Method 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_{\text{events}}$</td>
<td>$\sigma_{e^+e^-}$ (nb)</td>
</tr>
<tr>
<td>88.279</td>
<td>29</td>
<td>0.34 ± 0.06</td>
</tr>
<tr>
<td>89.277</td>
<td>42</td>
<td>0.64 ± 0.10</td>
</tr>
<tr>
<td>90.277</td>
<td>52</td>
<td>0.86 ± 0.12</td>
</tr>
<tr>
<td>91.030</td>
<td>136</td>
<td>1.08 ± 0.09</td>
</tr>
<tr>
<td>91.278</td>
<td>161</td>
<td>1.01 ± 0.08</td>
</tr>
<tr>
<td>91.529</td>
<td>156</td>
<td>0.98 ± 0.08</td>
</tr>
<tr>
<td>92.277</td>
<td>44</td>
<td>0.68 ± 0.10</td>
</tr>
<tr>
<td>93.276</td>
<td>18</td>
<td>0.29 ± 0.07</td>
</tr>
<tr>
<td>94.278</td>
<td>13</td>
<td>0.15 ± 0.04</td>
</tr>
</tbody>
</table>

The choice of $\delta_{\text{max}}$ and $\Delta_{\text{max}}$ has to done bearing in mind that high values of these cuts make the formula less precise while low values make the measurement sensitive to finite resolution of the detector. After a careful study of the performance of our calorimeter we chose $\delta_{\text{max}} = 10^\circ$, and $\Delta_{\text{max}} = 15^\circ$, corresponding to $k_{\text{max}} = 7.3$ GeV. We have studied the variation in cross section, as measured using only the three energy points close to the $Z^0$ peak, and as predicted by the fitting function changing the $\Delta_{\text{max}}$ and $\delta_{\text{max}}$ cuts between $5^\circ$ and $15^\circ$. There is agreement within 1% between prediction and experiment. We estimate a 2% error to the theoretical prediction of the cross section in this second method.

The cross sections used in the fit are also given in table 1. Note that since somewhat more restrictive cuts were required to allow use of the formula, the measured cross sections are smaller than those used in the peak subtraction method. Fitting the data with $M_Z$ and $F_Z$ fixed to the values we determined from the hadronic cross section [1] we obtain (fig. 1) $\Gamma_{e^+e^-} = 79.0 \pm 2.4 \text{(stat)} \pm 1.1 \text{(syst)} \pm 1.0 \text{(theory)}$ MeV. The difference between methods 1 and 2 is partially statistical due to the exclusion of data away from the peak in method 1. The remaining difference is slightly larger than the “theory errors” estimated. We consider method 1 to be more reliable.

5. Partial width for $Z^0 \rightarrow \mu^+\mu^-$

The $e^+e^-\rightarrow \mu^+\mu^- + \gamma$ cross section and its statistical error measured as a function of $\sqrt{s}$ are shown in
1.5
10
0.5
0
Z° \rightarrow \mu^+ \mu^-
\sqrt{s} (GeV)

Fig. 2. Measured cross sections as a function of the CM energy for the reaction $e^+e^-\rightarrow\mu^+\mu^-$. The curve is the fit to the data to obtain $\Gamma_R$.

Table 2. We fitted these data using an analytic form for the $Z^0$ cross section [11], and obtained $M_Z = 91.11 \pm 0.13$ GeV and $\Gamma_Z = 2.49 \pm 0.28$ GeV which is in excellent agreement with our previous measurements of the hadronic final state [1]. Given this agreement, we fit the data by fixing the mass and width of the $Z^0$ to the values determined from our fit to the hadronic cross section. The measured $e^+e^-\rightarrow\mu^+\mu^-(\gamma)$ cross sections and the fitted function are shown in fig. 2. Using the $\mu^+\mu^-$ data alone, we find

$$\Gamma_R = \sqrt{\Gamma_{ee} \Gamma_{\mu\mu}}$$

$$= 84.3 \pm 2.4 \text{(stat)} \pm 1.2 \text{(syst)} \text{ MeV}.$$ 

The statistical error quoted above includes a contribution of 1.4 MeV from the statistical error in our measured value of $\Gamma_Z$.

6. Average leptonic width

The correct determination of the average leptonic width, and its error, requires that the correlations between the errors in $\Gamma_{ee}$ and in $\Gamma_R$ be taken into account. The statistical errors of 1.6 MeV on the partial width for $e^+e^-$ final states, and of 1.4 MeV on the partial width for $\mu^+\mu^-$ final states, which are due to the statistical error on our measurement of $\Gamma_Z$ [1], are completely correlated. The systematic errors on $\Gamma_{ee}$ and $\Gamma_R$ both contain a 0.85% contribution from the systematic error on luminosity. These errors are also completely correlated for the two measurements.

We averaged the data from the two leptonic channels, assuming universality, and obtained

$$\Gamma_{ee} = 83.0 \pm 2.1 \pm 1.1 \text{ MeV}.$$ 

If we do not assume universality, we find $\Gamma_{\mu\mu} = 87.6 \pm 5.6$ MeV using the measured value of $\Gamma_{ee}$. The error quoted includes both statistical and systematic errors.

7. Simultaneous fit to lepton and hadron data

We have made a simultaneous fit to our cross sections for hadron [1], $e^+e^-$, and $\mu^+\mu^-$ production. The fit is model independent with $M_Z$, $\Gamma_{had}$, $\Gamma_{\mu\mu}$ and $\Gamma_{inv}$ as free parameters. As before, we have used the analytical forms for the $Z^0$ cross section given in ref. [11]. These include initial state radiation and a Breit-Wigner with an energy dependent width. We find, with a $\chi^2 = 17$ for 18 degrees of freedom,

$$M_Z = 91.156 \pm 0.026 \pm 0.030 \text{ GeV},$$

$$\Gamma_{had} = 1.744 \pm 0.053 \text{ GeV},$$

$$\Gamma_{\mu\mu} = 82.8 \pm 2.4 \text{ MeV},$$

$$\Gamma_{inv} = 537 \pm 48 \text{ MeV}.$$ 

If we assume the partial width of the $Z^0$ to neutrino pairs from the standard model, this value of $\Gamma_{inv}$ yields the number of neutrinos $N_\nu = 3.23 \pm 0.29$. This value should be compared with our determination within the standard model using the hadron data alone of $N_\nu = 3.29 \pm 0.17$.

8. Determination of $g_A$ and $g_V$

Using our $e^+e^-\rightarrow\mu^+\mu^- (\gamma)$ event sample, we have also measured the forward–backward charge asymmetry $A_{FB}$ defined as

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}.$$ 

By fitting $d\sigma/d(\cos \theta)$ to our data sample and extrapolating $\cos \theta$ to the full range we obtained

$$A_{FB}(\sqrt{s} = 89.94 \text{ GeV}) = - (25.0 \pm 15.2) \%,$$
Fig. 3. Measured forward–backward charge asymmetry $A_{FB}$ as a function of the CM energy for the reaction $e^+e^-\rightarrow\mu^+\mu^-$. The curve is the prediction of the standard model.

$$A_{FB}(\sqrt{s} = 91.03\,\text{GeV}) = -(9.0 \pm 10.7)\%,$$

$$A_{FB}(\sqrt{s} = 91.28\,\text{GeV}) = (17.9 \pm 8.4)\%,$$

$$A_{FB}(\sqrt{s} = 91.53\,\text{GeV}) = (8.7 \pm 10.2)\%,$$

$$A_{FB}(\sqrt{s} = 93.09\,\text{GeV}) = (8.2 \pm 11.7)\%,$$

Fig. 3 shows the measured asymmetries compared with values predicted by the standard model ($M_{\text{top}} = 100\,\text{GeV}$ and $M_H = 100\,\text{GeV}$).

Using the equation

$$\Gamma_{\text{ee}} = \frac{G_F M_Z^2}{6\sqrt{2}\pi} (g_A^2 + g_V^2),$$

we found

$$g_A^2 + g_V^2 = 0.250 \pm 0.007.$$  

From a fit to our asymmetry data and $\Gamma_{\text{ee}}$, including QED radiative corrections [12] and using the $Z^0$ mass we have previously measured [1], we obtained:

$$g_A = -0.495^{+0.007}_{-0.007}, \quad g_V = -0.066^{+0.046}_{-0.027},$$

where the errors include systematics. Note that data from other experiments [13–17] are used to determine the signs. Fig. 4 compares our determination of $g_A$ and $g_V$ to previous measurements [13–18].

9. Conclusion

We have measured $\Gamma_{\text{ee}}$ in both the $e^+e^-$ and $\mu^+\mu^-$ channels. The average result of

$$\Gamma_{\text{ee}} = 83.0 \pm 2.1 \pm 1.1\,\text{MeV}$$

is in good agreement with the expectation of the standard model. Combining our leptonic and hadronic measurements, we get a model independent determination of the number of neutrino species of $3.23 \pm 0.29$. We have also measured the forward–backward charge asymmetry in $\mu^+\mu^-$ production for 5 values of $\sqrt{s}$. The asymmetry is consistent with the standard model and allows us to determine the axial vector and vector couplings of the leptons to the $Z^0$:

$$g_A = -0.495^{+0.007}_{-0.007}, \quad g_V = -0.066^{+0.046}_{-0.027}.$$  

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References

A. Salam, Elementary particle theory, ed. N. Svartholm
[5] L3 Collab., B. Adeva et al., The construction of the L3
Workshop on Z physics at LEP, eds. G. Altarelli, R. Kleiss
and C. Verzegnassi, CERN Report 89-08 (CERN, Geneva,
programs supplied to L3 by the authors.
LEP, eds. G. Altarelli, R. Kleiss and C. Verzegnassi, CERN
Report 89-08 (CERN, Geneva, 1989), Vol. III, p. 69,
M. Caffo, E. Remiddi and F. Semeria, in: Z physics at LEP,
CERN Report 89-08, eds. G. Altarelli, R. Kleiss and C.
A. Borelli et al., preprint CERN-TH 5441/89.
D. Bardin et al., ZBIZON, a program package for the
precision calculation of observables for the process
\( \epsilon^+ \epsilon^- \rightarrow f^+ f^- \) around the Z peak, L3 Internal Note 679
(September 1989), unpublished;
D. Bardin et al., Berlin-Zeuthen preprint PHE 89-19, to be
published.
1663;
365;
CELLO Collab., H.J. Behrend et al., Z. Phys. C 16 (1983) 301;
1941;
1831;
2352.
(1976) 315.
W. Krenz, Aachen University Report No. PITHA 84/42
(1984), unpublished;
(1989) 539.