Measurement of $g_A$ and $g_V$, the Neutral Current Coupling Constants to Leptons.

The L3 Collaboration

CM-P00065272

ABSTRACT

We have measured both the rates and the forward-backward asymmetry of $l^+l^-$ from $Z^0 \rightarrow l^+l^-$ (where $l = \mu, \tau$) with the L3 detector. We obtained $\Gamma_{ll} = 88 \pm 4 \pm 3$ MeV and the vector neutral current coupling constant, $g_V = 0.00 \pm 0.07$ and the axial vector neutral current coupling constant, $g_A = -0.515 \pm 0.015$

L3 Preprint #003
November 24, 1989
Introduction

The study of leptonic decays of vector mesons has a long and successful history in providing direct comparison between experiment and theory. In the late sixties, the measurement\(^1\) of \(\rho, \omega\) and \(\phi \rightarrow e^+e^-\) or \(\mu^+\mu^-\) provided us with direct checks of the predictions of SU(3). The discoveries\(^2\) of \(J\) and \(\Upsilon\) via \(J \rightarrow e^+e^-\) and \(\Upsilon \rightarrow \mu^+\mu^-\) demonstrated the importance of precise experiments on leptonic final states. The measurements of \(\Gamma_{J \rightarrow e\ell\ell}\) and \(\Gamma_{\Upsilon \rightarrow \mu\mu}\) support the concept that quarks and leptons are grouped into families. In this paper, we report on our measurements of the rates and the forward-backward charge asymmetries of the decays \(Z^0 \rightarrow \mu^+\mu^-\), and \(\tau^+\tau^-\). This provides us with a determination of the partial width of the \(Z^0\) into charged leptons \(\Gamma_H\) and the vector \(g_V\) and axial vector \(g_A\) neutral current coupling constants.

The neutral current coupling constants \(g_V\) and \(g_A\) are fundamental quantities describing the neutral current \(j_\mu\) via:

\[
j_\mu = \bar{l}(g_V \gamma_\mu + g_A \gamma_\mu \gamma^5) l
\]

(1)

The cross section for \(e^+e^- \rightarrow (Z^0, \gamma) \rightarrow l^+l^-\) with \(l = \mu, \tau\) can be written as\(^3\):

\[
\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} \left\{ \left[ 1 + 2g_V^2 Re(\chi) + (g_V^2 + g_A^2)^2 |\chi|^2 \right](1 + \cos^2 \theta) \right. \\
\quad \left. + \left[ 2g_A^2 Re(\chi) + 4g_V^2 g_A^2 |\chi|^2 \right] 2 \cos \theta \right\},
\]

(2)

where \(\theta\) is the polar angle of the \(\mu^-\) or \(\tau^-\) with respect to the \(e^-\) direction and

\[
\chi = \frac{G_\mu M_Z^2}{2\sqrt{2}\pi \alpha} \frac{s}{(s - M_Z^2) + i M_Z \Gamma_Z}
\]

is the \(Z^0\) propagator. For the determination of \(g_V\) and \(g_A\) it is important to note the following:

1) Near the mass of the \(Z^0\), the rate of \(Z^0 \rightarrow l^+l^-\) is a measure of \(g_V^2 + g_A^2\).

2) Similarly, the forward-backward charge asymmetry of \(Z^0 \rightarrow l^+l^-\) is a measure of the product \(g_V^2 - g_A^2\).

3) Due to the strong dependence of \(|\chi|^2\) on \(s\) in equation (2), it is much easier to obtain \(g_V\) and \(g_A\) near the \(Z^0\) pole than it was at the earlier \(e^+e^-\) experiments at PETRA and PEP, where only the terms \(g_V^2 Re(\chi)\) and \(g_A^2 Re(\chi)\) were contributing.

The L3 detector\(^4\) is a \(4\pi\) detector with a central vertex chamber, a electromagnetic calorimeter, a uranium proportional chamber hadron calorimeter, and a high accuracy muon chamber system. All these detectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 Tesla along the beam direction. Luminosity is measured by 8 radial layers of BGO crystals at small angle (24.7 mrad \(< \theta < 68.8\) mrad) on each side of the interaction point.
Measurement of $\tau$ Pairs

The event selection for the process $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$ was based on the electromagnetic and hadron calorimeters and on the muon chambers. In Fig. 1 an $e^+\mu^-$ event is shown as it appears in the L3 detector in the plane perpendicular to the beam axis. We interpret this event as originating from the following interaction and subsequent decays:

$$e^+e^- \rightarrow Z^0 \rightarrow \tau^+\tau^- \rightarrow e^+\nu_\tau\bar{\nu}_\tau + \mu^-\bar{\nu}_\mu\nu_\mu$$

The negatively charged muon has a momentum of $12.75 \pm 0.21$ GeV/c as measured by the muon detector, corrected for an average energy loss in the material between the primary vertex and the muon chambers.

The positron in the event of Fig. 1 is detected as a localised cluster of $25.75 \pm 0.52$ GeV in the electromagnetic calorimeter. The pattern recognition program searching for local maxima inside the 43 activated BGO crystals finds only one maximum and this particular cluster is labelled as consisting of one shower peak due to one particle.

For the $\tau$ measurement, all $Z^0$ candidates selected by our reconstruction program have been scanned by physicists. The main object of this scan was to check the detector performance, the reliability of the reconstruction and to remove background and cosmic ray events. The $\tau$'s have been extracted from the resulting $Z^0$ candidates by applying the following criteria:

1) The energy deposited in the electromagnetic calorimeter had to be greater than 10 GeV or the sum of the energies within the electro-magnetic and the hadron calorimeters had to be greater than 15 GeV,

2) The energy deposited in the electromagnetic calorimeter had to be greater than 4 GeV and smaller than 60 GeV,

3) The polar angle $\theta$ of the thrust axis of the event had to satisfy $|\cos \theta| < 0.7$,

4) The number of shower peaks in the electromagnetic calorimeter had to be smaller than 12.

Criterion 1) is the same as the energy trigger condition during data-taking, 2) removes events of the type $e^+e^- \rightarrow (Z^0, \gamma) \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$, 3) restricts the events to be contained within the barrel of the BGO detector. Criterion 4) restricts the final state multiplicity, thus removing the pure hadronic events from the sample.

The events selected by criteria 1) to 4) were independently inspected by two groups of physicists to remove remaining backgrounds. We thus obtained a sample of 83 $\tau$ events. The acceptance was calculated to be $0.51 \pm 0.02$ by applying the above mentioned criteria to a sample of Monte-Carlo generated $\tau$'s. An estimate was made of the scanning efficiency of the physicists by scanning the Monte-Carlo generated tau events which passed the selection criteria; 2% of these were lost.
because of wrong classification. The number of pure hadronic events inside the \( \tau \) sample was estimated to be \( 6.8 \pm 4 \) events, by applying the criteria to a sample of Monte Carlo generated hadronic \( Z^0 \) decays.

As a further check we determined the number of events having a single muon coming directly from the interaction point in one hemisphere of the detector and collimated electromagnetic and hadronic energy in the opposite hemisphere. There are 24 such events in our sample of 83 \( \tau \)-pair candidates. These events are interpreted as being of the type:

\[
e^+e^- \rightarrow \tau^+\tau^- \rightarrow \mu^+ + X
\]

where \( X \) is either an electron (or positron) or hadrons. Comparing the number of events with a well-fitted isolated muon track for data and Monte-Carlo we obtain \( BR(\tau \rightarrow \mu X) = (20.1 \pm 4.4)\% \) in good agreement with the world average\(^7\) of \( (17.8 \pm 0.4)\% \).

To perform a consistent analysis for the \( Z^0 \rightarrow \tau^+\tau^- \) and \( \mu^+\mu^- \) we fixed the mass and width of the \( Z^0 \) to the values as determined from our fit to the hadronic cross section\(^8\), \( M_Z = 91.132 \) GeV and \( \Gamma_Z = 2.588 \) GeV. For the channels \( Z^0 \rightarrow \mu^+\mu^- \), and \( \tau^+\tau^- \) fits to the data are made, using the analytic form for the \( Z^0 \) cross section as given by Cahn and Borelli et al.\(^9\) and leaving only the partial width to \( \tau\tau \) and \( \mu\mu \) as free parameters respectively.

In Fig. 2 we show the cross sections as function of energy\(^10\) with the result of the fit to the data points. The value for the partial width is:

\[
\Gamma_{\tau\tau} = 84 \pm 5 \pm 4 \text{ MeV},
\]

assuming \( e - \tau \) universality. The systematic error has been estimated from the luminosity measurements, event selection, acceptance calculations and background contributions.

**Measurement of \( \mu \) Pairs**

The muon pairs from the reaction

\[
e^+e^- \rightarrow Z^0 \rightarrow \mu^+\mu^-
\]

were selected using a combination of cuts on muon momentum, vertex position and scintillator timing relative to the beam crossing\(^8\). With these cuts we selected 97 muon pairs. We estimated a total systematic error of 3\%. In order to determine the partial width of the \( Z^0 \) into \( \mu^+\mu^- \) we have fitted the data fixing the mass and the width of the \( Z^0 \) and assuming \( e - \mu \) universality. The result of the fit was found
to be:
\[ \Gamma_{\mu\mu} = 92 \pm 5 \pm 3 \text{ MeV}. \]

The same kind of fit when applied to the average of the \( \mu \) and \( \tau \) data (assuming \( e - \mu - \tau \) universality) gives for the partial width of the \( Z^0 \) into a pair of leptons:
\[ \Gamma_{\ell\ell} = 88 \pm 4 \pm 3 \text{ MeV}. \]

The values of the averaged \( \mu \) and \( \tau \) cross sections together with the curve from the fit is shown in Fig. 3.

This value is in agreement with the prediction of 83.3 MeV of the standard model at our measured \( Z^0 \) mass value and assuming the mass of the top quark to be less than 100 GeV. It has to be noted that our previous measurement\(^8\) of \( \Gamma_{ee} \):
\[ \Gamma_{ee} = 88 \pm 9 \pm 7 \text{ MeV}, \]
is consistent with our current results and including \( \Gamma_{ee} \) does not change the value of \( \Gamma_{\ell\ell} \).

Our result \( \Gamma_{\ell\ell} \) can be interpreted in terms of the axial \( g_A \) and vector \( g_V \) couplings of the \( Z^0 \) to leptons\(^{11} \) using the relation:
\[ \Gamma_{\ell\ell} = \frac{G_F M_Z^3}{6\sqrt{2\pi}} (g_A^2 + g_V^2) \]
which, using our measured values of \( M_Z \) and \( \Gamma_{\ell\ell} \), corresponds to a circular band, including systematic errors, in the \( g_A - g_V \) plane satisfying the equation:
\[ g_A^2 + g_V^2 = 0.266 \pm 0.014 \]
(3)

Measurement of Forward-Backward Charge Asymmetry

To obtain \( |g_V| \) and \( |g_A| \) we measure the forward-backward charge asymmetry \( A_{FB} \) defined as:
\[ A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}, \]
where \( \sigma_F = 2\pi \int_0^{0.7} d(\cos \theta) \frac{d\sigma}{d\Omega} \) is number of \( \mu^+\mu^- \) and \( \tau^+\tau^- \) events with \( \mu^- \) and \( \tau^- \) in the \( \theta \) region of \( 0. \leq \cos \theta \leq 0.7 \) and \( \sigma_B = 2\pi \int_{-0.7}^0 d(\cos \theta) \frac{d\sigma}{d\Omega} \) is number of \( \mu^+\mu^- \) and \( \tau^+\tau^- \) events with \( \mu^- \) and \( \tau^- \) within \( -0.7 \leq \cos \theta \leq 0 \).
We have analysed a total of 241 $\mu^+\mu^-$ and 24 $\tau^+\tau^-$ events (those $\tau$ pairs with one muon have the charge of the $\tau$ established) and obtain:

$$A_{FB}(\sqrt{s} = 90.00 \text{ GeV}) = (-40 \pm 19)\%$$

$$A_{FB}(\sqrt{s} = 91.26 \text{ GeV}) = (-1 \pm 7)\%$$

$$A_{FB}(\sqrt{s} = 92.94 \text{ GeV}) = (+23 \pm 19)\%$$

The charge asymmetry can be calculated for given $Z^0$ mass, $\Gamma_Z$, $g_A$ and $g_V$. A fit, including QED corrections, was made\textsuperscript{12} with $M_Z = 91.132$ GeV, $\Gamma_Z = 2.588$ GeV and $g_A$ and $g_V$ constrained to equation (3). The result including systematic errors is:

$$|g_A| = 0.515 \pm 0.015$$

$$g_V = 0.00 \pm 0.07$$

This result is insensitive to the errors on $M_Z$ ($\pm 0.057$ GeV) and $\Gamma_Z$ ($\pm 0.137$ GeV).

When our measurements are combined with the earlier purely leptonic measurements from the $e^+e^-$ machines PETRA and PEP\textsuperscript{13}, the $\nu$ experiments at CERN\textsuperscript{14} and BNL\textsuperscript{15} and the reactor experiment of Reines et al.\textsuperscript{16}, we are able to choose the sign of the coupling constants. Figure 4 shows the enlarged region in the $g_A - g_V$ plane around $g_A \sim -0.5$ where previous measurements\textsuperscript{13,14,15,16,17} and our result coincide. Our final result becomes:

$$g_A = -0.515 \pm 0.015$$

$$g_V = 0.00 \pm 0.07$$

Acknowledgments

We wish to thank CERN for its hospitality and help. We want particularly to express our gratitude to the LEP division: it is their excellent achievement which made this experiment possible. We acknowledge the support of all the funding agencies which contributed to this experiment.

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§ Supported by the German Bundesministerium für Forschung und Technologie
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     Note in Fig. 4, that in order to compare with our result, we have plotted their result by adding in quadrature their statistical and systematic errors.


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FIGURE CAPTIONS:

Fig.1 An event of the type $e^+e^- \rightarrow e^+\mu^- + \text{neutrals}$ as seen in the plane perpendicular to the beam axis. The muon momentum is $10.61 \pm 0.14$ GeV/c as measured by the muon chambers (A). Adding the measured energy loss in the hadron calorimeter (B) of $1.68 \pm 0.70$ GeV and in 3 BGO crystals (C) of $360 \pm 19$ MeV the original muon energy is $12.65 \pm 0.71$ GeV. This value has to be compared with $12.75 \pm 0.21$ GeV/c, being the measurement of the muon detector, corrected for an average energy loss in the material between the primary vertex and the muon chambers. The electromagnetic cluster opposite the muon track has an energy deposited in the BGO crystals of $25.75 \pm 0.52$ GeV.

Fig.2 Measured cross sections as function of the c.m. energy for the the reaction $e^+e^- \rightarrow \tau^+\tau^-$. The drawn curve is the fit to the data to obtain $\Gamma_{\tau\tau}$ (see text).

Fig.3 Averaged measured cross sections for the the reactions $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$ as function of the c.m. energy. The drawn curve is the fit to the data to obtain $\Gamma_{\mu\mu}$ (see text).

Fig.4 Results obtained from neutrino experiments and the $e^+e^-$ experiments expressed in $1\sigma$ limits on $g_A$ and $g_V$. Area (A) is the result of the CHARM collaboration\textsuperscript{14}, area (B) is the combined $e^+e^-$ results from PETRA and PEP\textsuperscript{13}, area (C) is the $\nu_\tau e$ result\textsuperscript{16} and area (D) is the BNL result\textsuperscript{15}. The black area represents our measurement.
Run # 40101 Events # 589

Figure 1
Figure 2
Figure 3
Figure 4