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A Measurement of the Z^0 Leptonic Partial Widths and the Vector and Axial Vector Coupling Constants

[redacted]

The L3 Collaboration

ABSTRACT

We have measured the partial widths of the Z^0 into lepton pairs, and the forward-backward charge asymmetry for the process $e^+e^- \rightarrow \mu^+\mu^-$ using the L3 detector at LEP. We obtain an average $\Gamma_{\ell\ell}$ 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: $g_V = -0.066^{+0.046}_{-0.027}$ and $g_A = -0.495^{+0.007}_{-0.007}$.

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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 $\Gamma_{\ell\ell}$, 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 $\Gamma_{\ell\ell}$ and of the Z^0 vector and axial vector couplings, g_V and g_A, to charged leptons. The results are based on our measurements of the $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$ cross sections and on the forward-backward charge asymmetry A_{FB} in $e^+e^- \rightarrow \mu^+\mu^-$. With the increased luminosity delivered by LEP ($\sim 1\ pb^{-1}$), we have increased the data sample sizes by a factor of five relative to our previous analysis [4]. The systematic errors also have been reduced by a careful study of the detector performance.

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 hadron 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 [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 total efficiency is determined to be 0.975 ± 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.

Event Selection

Events from the process $e^+e^- \to e^+e^-(\gamma)$ 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 $e^+e^- \to e^+e^-(\gamma)$ 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 ± 0.010 for events within the defined angular region for the cuts described above.

For the same cuts, the background from $\tau\tau$ and $e^+e^- \to$ *hadrons* was found to be less than 0.3% of the final e^+e^- event sample. The background due to $e^+e^- \to \gamma\gamma$ has been calculated according to [8], and has been subtracted from the data at each value of $\sqrt{s}$. For $\sqrt{s} = M_{Z^0}$, this background amounted to 1.8% of the signal cross section. The contribution of the "two photon process" $e^+e^- \to e^+e^-e^+e^-$ 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 $e^+e^- \to e^+e^-(\gamma)$ cross section.

Events from the process $e^+e^- \to \mu^+\mu^-(\gamma)$ 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, and

(4) acollinearity angle between the two muons less than 15°.

In order to include final state radiation we define E_μ 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_μ 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:

(6a) the times for both muons had to be within ± 2.5 ns of the beam crossing time and their difference less than 2.5 ns, or

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

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

From the analysis of simulations for the process $e^+e^- \to \tau^+\tau^- \to \mu^+\mu^- + \nu's$ [9], we estimate a contamination 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 process) have been found to give negligible contributions.

The acceptance for $e^+e^- \to \mu^+\mu^-(\gamma)$ was calculated 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 ± 0.009 (Monte Carlo statistical error). A correction 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 luminosity 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 $e^+e^- \to \mu^+\mu^-$ cross section of 2.8%.

Partial Width for $Z^0 \to e^+e^-$

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 Γ_{ee}, could be significant. We have therefore used two methods to determine Γ_{ee} from our electron data. In the first and most direct method, we subtracted the contribution of the t channel γ 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 formula given in [10] was used. This has the advantage 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 Γ_{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 background from $e^+e^- \to \gamma\gamma$ 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, $\sigma_{MC}^{e^+e^-}$ and $\sigma_{MC}^{\mu^+\mu^-}$, from Monte Carlo simulations [7,9] and we calculated the s-channel contribution to the cross section as $\sigma_{Z^0} = \sigma_{exp} - (\sigma_{MC}^{e^+e^-} - \sigma_{MC}^{\mu^+\mu^-})$. We then find

$$\Gamma_{ee} = 81.1 \pm 2.8(stat) \pm 1.2(syst) \pm 0.7(theory) \text{ MeV}.$$

The statistical error quoted above includes a contribution of 1.6 MeV from the statistical error on the measured total width of the Z^0, as determined from our hadron data ($\Gamma_Z = 2.539 \pm 0.054$ GeV, $M_Z = 91.160 \pm 0.038$ 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 γ and the Z^0 exchange diagrams in the s and t channels with interference terms. Soft radiation is accounted 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 $k > k_{max}$) emitted at large angles ($\delta > \delta_{max}$) with respect to the direction 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 rejected by an acollinearity cut Δ_{max} on the final state e^+e^-. Choosing Δ_{max} effectively sets the k_{max} used. The choice of δ_{max} and Δ_{max} has to be 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 $\delta_{max} = 10°$, and $\Delta_{max} = 10°$, corresponding to $k_{max} = 7.3$ 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 Δ_{max} and δ_{max} cuts between 5° and 15°. 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 Γ_Z fixed to the values we determined from the hadronic cross section [1] we obtain (Fig. 1) $\Gamma_{ee} = 79.0 \pm 2.4(stat) \pm 1.1(syst) \pm 1.(theory)$ 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.

TABLE 1

Measured e^+e^- Cross Sections for Methods 1 and 2

$\sqrt{s}$ (GeV)	N_{events} method 1	$\sigma_{e^+e^-}$ (nb) method 1	N_{events} method 2	$\sigma_{e^+e^-}$ (nb) method 2
88.279	29	0.34 ± 0.06	26	0.30 ± 0.06
89.277	42	0.64 ± 0.10	39	0.60 ± 0.10
90.277	52	0.86 ± 0.12	50	0.83 ± 0.12
91.030	136	1.08 ± 0.09	129	1.02 ± 0.09
91.278	161	1.01 ± 0.08	156	0.98 ± 0.08
91.529	156	0.98 ± 0.08	153	0.96 ± 0.08
92.277	44	0.68 ± 0.10	44	0.68 ± 0.10
93.276	18	0.29 ± 0.07	15	0.24 ± 0.07
94.278	13	0.15 ± 0.04	11	0.12 ± 0.04

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.

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 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:

$$\Gamma^{\mu}_{\ell\ell} = \sqrt{\Gamma_{ee}\Gamma_{\mu\mu}} = 84.3 \pm 2.4(stat) \pm 1.2(syst) \quad \text{MeV}$$

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

TABLE 2

Number of events and cross sections for $e^+e^- \rightarrow \mu^+\mu^-$

$\sqrt{s}$ (GeV)	$\mu^+\mu^-(\gamma)$ evts	$\sigma_{\mu^+\mu^-}$ (nb)
88.279	5	0.12 ± 0.05
89.277	8	0.29 ± 0.10
90.277	51	1.15 ± 0.16
91.030	82	1.44 ± 0.16
91.278	147	1.44 ± 0.12
91.529	110	1.32 ± 0.13
92.309	33	0.97 ± 0.17
93.276	32	0.70 ± 0.12
94.278	16	0.38 ± 0.09

Average Leptonic Width

The correct determination of the average leptonic width, and its error, requires that the correlations between the errors in Γ_{ee} and in $\Gamma^{\mu}_{\ell\ell}$ 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 Γ_Z [1], are completely correlated. The systematic errors on Γ_{ee} and $\Gamma^{\mu}_{\ell\ell}$ 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:

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

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

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, Γ_{had}, $\Gamma_{\ell\ell}$, and Γ_{inv} as free parameters. As before, we have used the analytical forms for the Z^0 cross section given in [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:

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

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

$$\Gamma_{\ell\ell} = 82.8 \pm 2.4 \text{ MeV}$$

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

If we assume the partial width of the Z^0 to neutrino pairs from the standard model, this value of Γ_{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 $N_\nu = 3.29 \pm 0.17$.

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 $\frac{d\sigma}{d(\cos\theta)}$ to our data sample and extrapolating $\cos\theta$ to the full range we obtained:

$$\begin{aligned} A_{FB}(\sqrt{s} = 89.94 \text{ GeV}) &= -25.0 \pm 15.2\% \\ A_{FB}(\sqrt{s} = 91.03 \text{ GeV}) &= -9.0 \pm 10.7\% \\ A_{FB}(\sqrt{s} = 91.28 \text{ GeV}) &= 17.9 \pm 8.4\% \\ A_{FB}(\sqrt{s} = 91.53 \text{ GeV}) &= 8.7 \pm 10.2\% \\ A_{FB}(\sqrt{s} = 93.09 \text{ GeV}) &= 8.2 \pm 11.7\% \end{aligned}$$

Fig. 3 shows the measured asymmetries compared with values predicted by the Standard Model ($M_{top} = 100$ GeV and $M_H = 100$ GeV).

Using the equation

$$\Gamma_{\ell\ell} = \frac{G_\mu M_Z^3}{6\sqrt{2}\pi}(g_A^2 + g_V^2)$$

we found

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

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

$$g_A = -0.495^{+0.007}_{-0.007}$$

$$g_V = -0.066^{+0.046}_{-0.027}$$

where the errors include systematics. Note that data from other experiments [13-17] are used to determine the signs. Figure 4 compares our determination of g_A and

g_V to previous measurements [13-18]

Conclusion

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

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

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 ± 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:

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

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FIGURE CAPTIONS:

*Fig.*1 Measured cross sections as a function of the c.m. energy for the reaction $e^+e^- \rightarrow e^+e^-$ for the polar angle region from 42° to 138°. The curve is the fit to the data obtained with Method 2 as described in the text.

*Fig.*2 Measured cross sections as a function of the c.m. energy for the reaction $e^+e^- \rightarrow \mu^+\mu^-$. The curve is the fit to the data to obtain $\Gamma^{\mu}_{\ell\ell}$.

*Fig.*3 Measured forward-backward charge asymmetry A_{FB} as a function of the c.m. energy for the reaction $e^+e^- \rightarrow \mu^+\mu^-$. The curve is the prediction of the standard model.

*Fig.*4 Results obtained from neutrino experiments and the e^+e^- experiments expressed as contours in g_A and g_V. Area (A) is the result of the CHARM collaboration (68% confidence level)[13], area (B) is the combined e^+e^- result from PETRA and PEP (95% confidence level)[14], area (C) is the reactor $\bar{\nu}_e e$ result (68% confidence level)[15], area (D) is the BNL result (68% confidence level)[16], and area E is the CHARM II result (68% confidence level)[18]. The black area represents our measurement based on the L3 measurements of $\Gamma_{\ell\ell}$ and the asymmetry (68% confidence level).

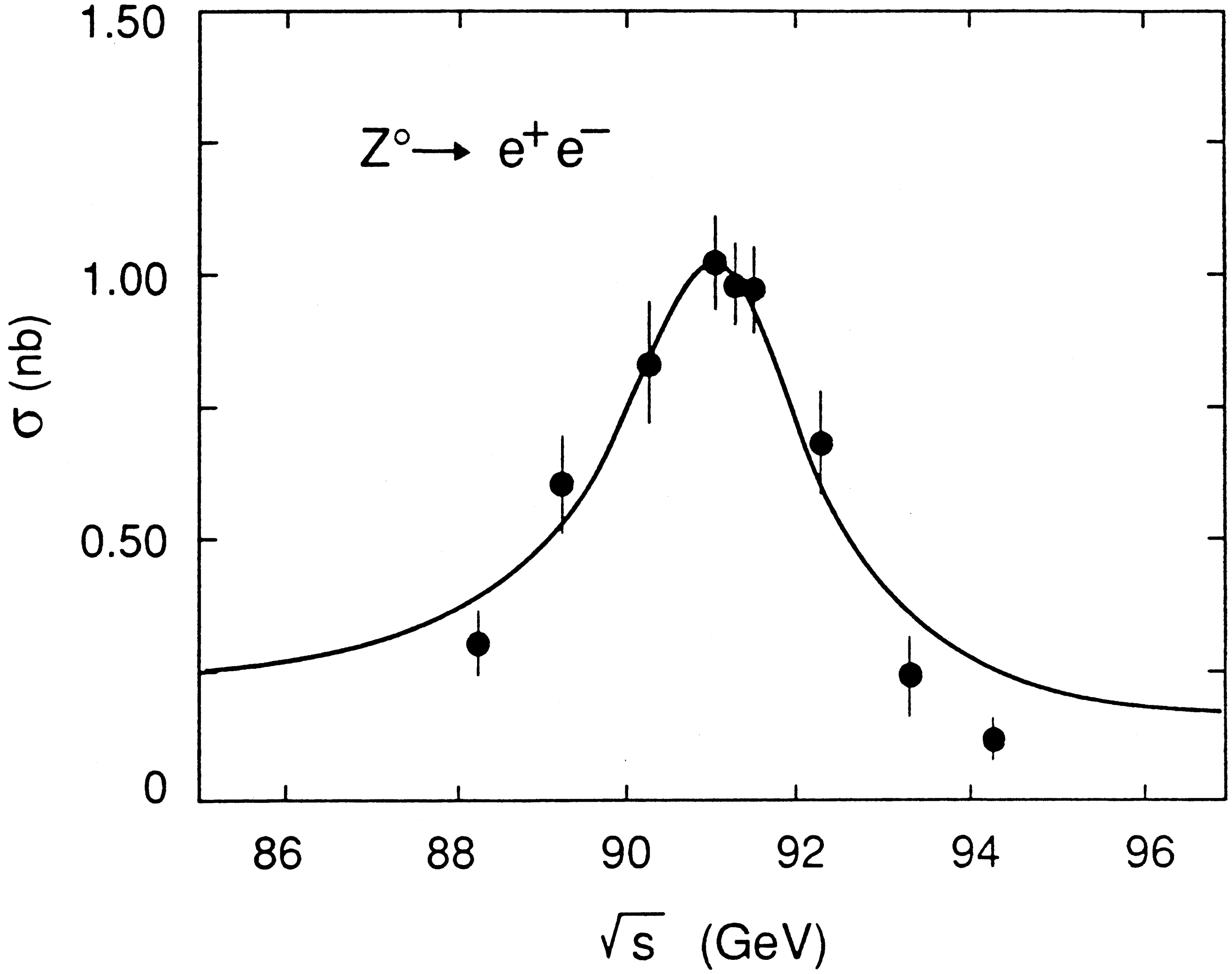

Figure 1

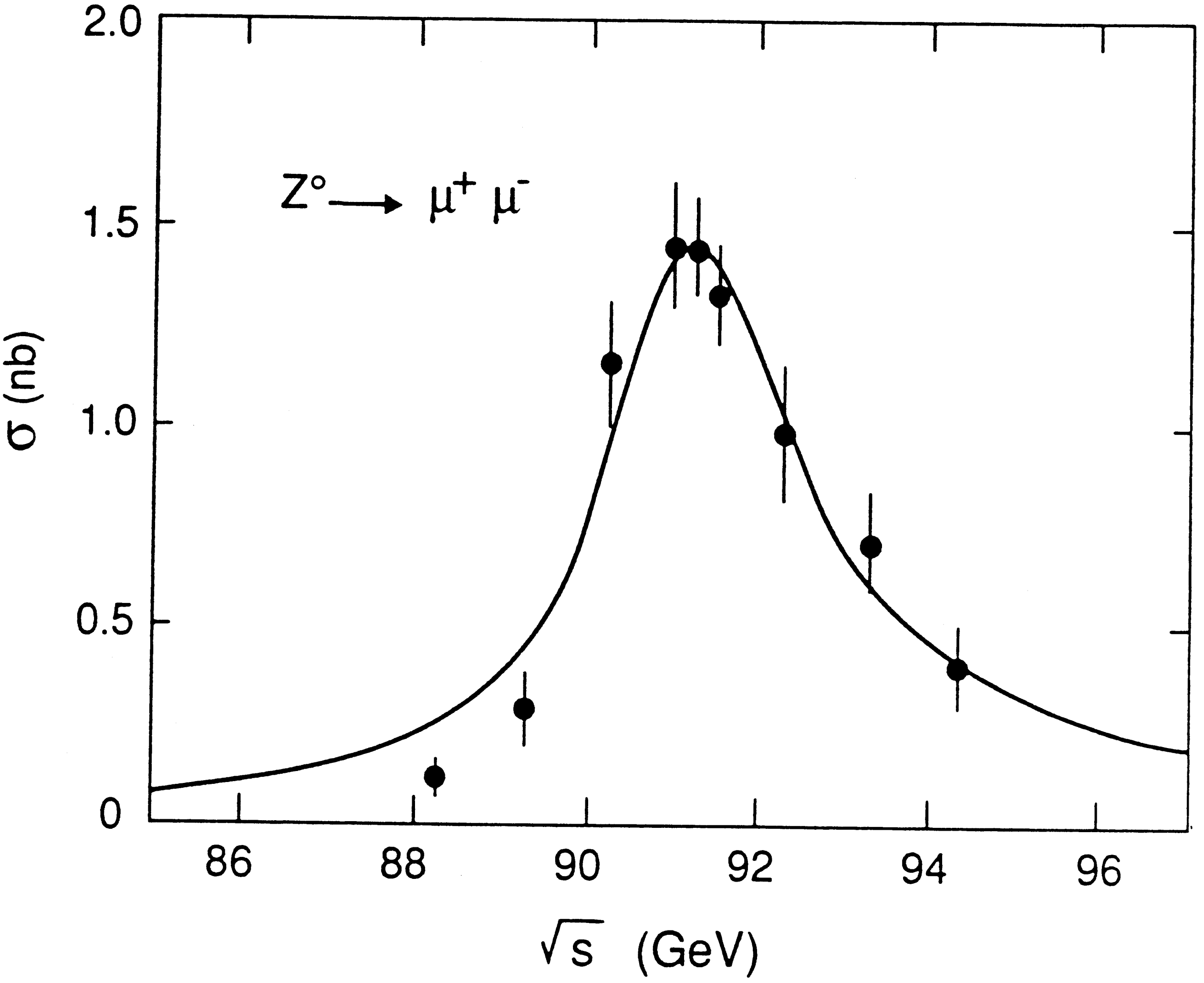

Figure 2

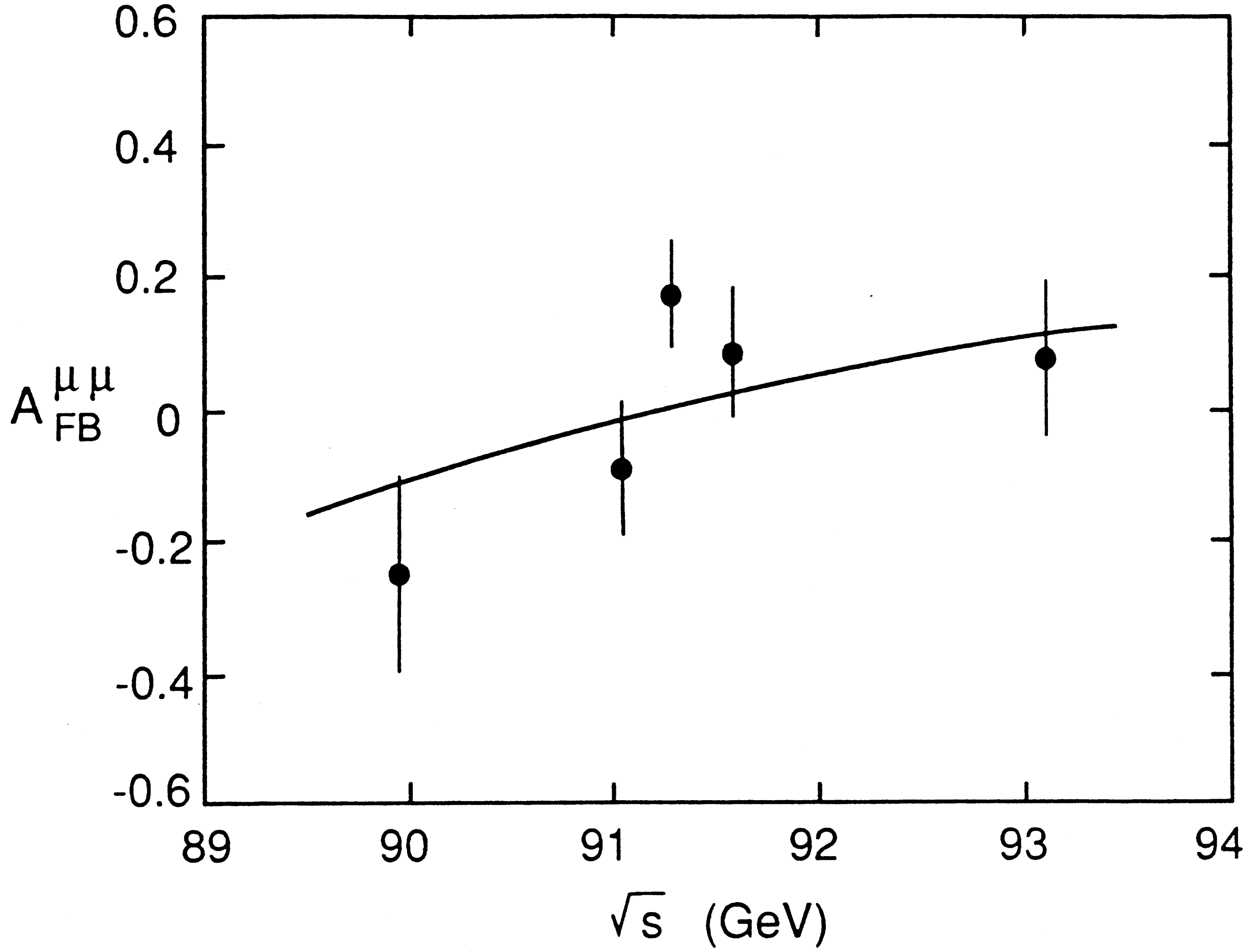

Figure 3

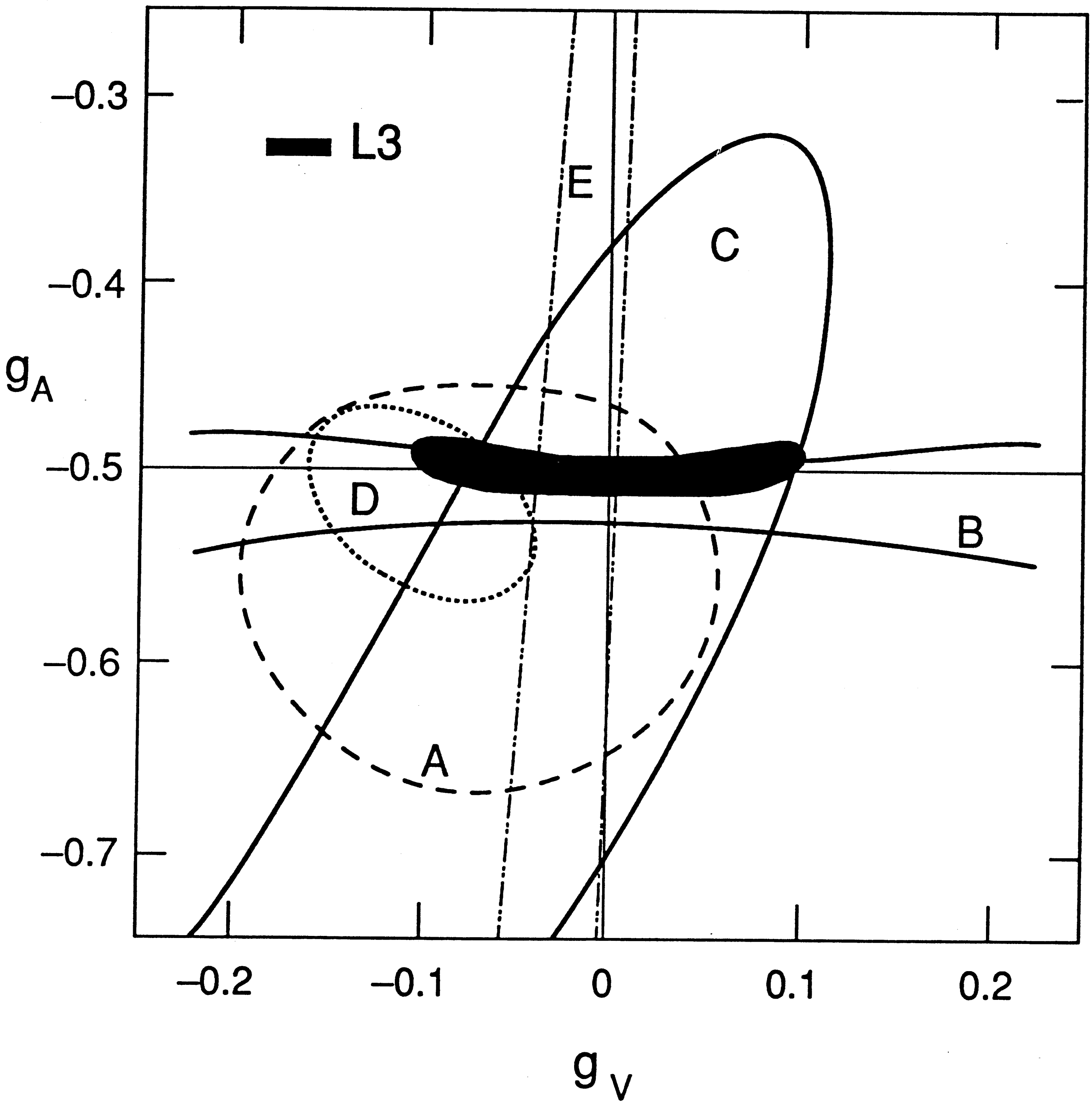

Figure 4