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Adeva, B.; Adriani, O.; Aguilar-Benitez, M.; Akbari, H.; Alcaraz, J.; Aloisio, A.; Alverson, G.; Alviggi, M.G.; Linde, F.L.

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A determination of electroweak parameters from $Z^0 \to \mu^+\mu^-(\gamma)$

L3 Collaboration

B. Adeva [a], O. Adriani [b], M. Aguilar-Benitez [c], H. Akbari [d], J. Alcaraz [c], A. Aloisio [e], G. Alverson [f], M.G. Alviggi [e], Q. An [g], H. Anderhub [h], A.L. Anderson [i], V.P. Andreev [j], T. Angelov [i], L. Antonov [k], D. Antreasyan [ℓ], P. Arce [c], A. Arefiev [m], T. Azemoon [n], T. Aziz [o], P.V.K.S. Baba [g], P. Bagnaia [p], J.A. Bakken [q], L. Baksay [r], R.C. Ball [n], S. Banerjee [o,g], J. Bao [d], L. Barone [p], A. Bay [s], U. Becker [i], J. Behrens [h], S. Beingessner [t], Gy.L. Bencze [u,r], J. Berdugo [c], P. Berges [i], B. Bertucci [p], B.L. Betev [k], A. Biland [h], R. Bizzarri [p], J.J. Blaising [t], P. Blömeke [v], B. Blumenfeld [d], G.J. Bobbink [w], M. Bocciolini [b], W. Böhlen [x], A. Böhm [v], T. Böhringer [y], B. Borgia [p], D. Bourilkov [k], M. Bourquin [s], D. Boutigny [t], J.G. Branson [z], I.C. Brock [α], F. Bruyant [a], C. Buisson [β], A. Bujak [γ], J.D. Burger [i], J.P. Burq [β], J. Busenitz [δ], X.D. Cai [g], C. Camps [v], M. Capell [n], F. Carbonara [e], F. Carminati [b], A.M. Cartacci [b], M. Cerrada [c], F. Cesaroni [p], Y.H. Chang [i], U.K. Chaturvedi [g], M. Chemarin [β], A. Chen [ε], C. Chen [ζ], G.M. Chen [ζ], H.F. Chen [η], H.S. Chen [ζ], M. Chen [i], M.L. Chen [n], G. Chiefari [e], C.Y. Chien [d], C. Civinini [b], I. Clare [i], R. Clare [i], G. Coignet [t], N. Colino [a], V. Commichau [v], G. Conforto [b], A. Contin [a], F. Crijns [w], X.Y. Cui [g], T.S. Dai [i], R. D'Alessandro [b], R. de Asmundis [e], A. Degré [t], K. Deiters [a,θ], E. Dénes [u], P. Denes [q], F. DeNotaristefani [p], M. Dhina [h], D. DiBitonto [δ], M. Diemoz [p], F. Diez-Hedo [a], H.R. Dimitrov [k], C. Dionisi [p], F. Dittus [κ], R. Dolin [i], E. Drago [e], T. Driever [w], D. Duchesneau [s], P. Duinker [w,a], I. Duran [a,c], H. El Mamouni [β], A. Engler [α], F.J. Eppling [i], F.C. Erné [w], P. Extermann [s], R. Fabbretti [h], G. Faber [i], S. Falciano [a,p], Q. Fan [g,ζ], S.J. Fan [λ], M. Fabre [h], J. Fay [β], J. Fehlmann [h], H. Fenker [f], T. Ferguson [α], G. Fernandez [c], F. Ferroni [p,a], H. Fesefeldt [v], J. Field [s], G. Finocchiaro [p], P.H. Fisher [d], G. Forconi [s], T. Foreman [w], K. Freudenreich [h], W. Friebel [θ], M. Fukushima [i], M. Gailloud [y], Yu. Galaktionov [m], E. Gallo [b], S.N. Ganguli [o], P. Garcia-Abia [c], S.S. Gau [ε], S. Gentile [p], M. Gettner [f], M. Glaubman [f], S. Goldfarb [n], Z.F. Gong [g,η], E. Gonzalez [c], A. Gordeev [m], P. Göttlicher [v], D. Goujon [s], C. Goy [t], G. Gratta [κ], A. Grimes [f], C. Grinnell [i], M. Gruenewald [κ], M. Guanziroli [g], A. Gurtu [o], L.J. Gutay [γ], H. Haan [v], S. Hancke [v], K. Hangarter [v], M. Harris [a], A. Hasan [g], C.F. He [λ], A. Heavey [q], T. Hebbeker [v], M. Hebert [z], G. Herten [i], U. Herten [v], A. Hervé [a], K. Hilgers [v], H. Hofer [h], H. Hoorani [g], L.S. Hsu [ε], G. Hu [g], G.Q. Hu [λ], B. Ille [β], M.M. Ilyas [g], V. Innocente [e,a], E. Isiksal [h], E. Jagel [g], B.N. Jin [ζ], L.W. Jones [n], P. Kaaret [q], R.A. Khan [g], Yu. Kamyshkov [m], D. Kaplan [f], Y. Karyotakis [t,a], M. Kaur [g], S. Khokhar [g], V. Khoze [j], D. Kirkby [κ], W. Kittel [w], A. Klimentov [m], A.C. König [w], O. Kornadt [v], V. Koutsenko [m], R.W. Kraemer [α], T. Kramer [i], V.R. Krastev [k], W. Krenz [v], J. Krizmanic [d], A. Kuhn [x], K.S. Kumar [μ], V. Kumar [g], A. Kunin [m], S. Kwan [f], A. van Laak [v], V. Lalieu [s], G. Landi [b], K. Lanius [a,θ], W. Lange [θ], D. Lanske [v], S. Lanzano [e], P. Lebrun [β], P. Lecomte [h], P. Lecoq [a], P. Le Coultre [h], I. Leedom [f], J.M. Le Goff [a], A. Leike [θ], L. Leistam [a], R. Leiste [θ], J. Lettry [h], P.M. Levchenko [j], X. Leytens [w], C. Li [η], H.T. Li [ζ], J.F. Li [g], L. Li [h], P.J. Li [λ], Q. Li [g], X.G. Li [ζ], J.Y. Liao [λ], Z.Y. Lin [η], F.L. Linde [α], D. Linnhofer [a], R. Liu [g], Y. Liu [g], W. Lohmann [θ], S. Lökös [r], E. Longo [p], Y.S. Lu [ζ], J.M. Lubbers [w], K. Lübelsmeyer [v], C. Luci [a], D. Luckey [ℓ,i], L. Ludovici [p], X. Lue [h], L. Luminari [p], W.G. Ma [η], M. MacDermott [h], R. Magahiz [r], M. Maire [t], P.K. Malhotra [o], R. Malik [g], A. Malinin [m], C. Maña [a,c], D.N. Mao [n], Y.F. Mao [ζ], M. Maolinbay [h], P. Marchesini [g], A. Marchionni [b], J.P. Martin [β], L. Martinez [c], F. Marzano [p],

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G.G.G. Massaro [w], T. Matsuda [i], K. Mazumdar [o], P. McBride [μ], T. McMahon [γ], D. McNally [h], Th. Meinholz [v], M. Merk [w], L. Merola [e], M. Meschini [b], W.J. Metzger [w], Y. Mi [g], M. Micke [v], U. Micke [v], G.B. Mills [n], Y. Mir [g], G. Mirabelli [p], J. Mnich [v], M. Möller [v], L. Montanet [a], B. Monteleoni [b], G. Morand [s], R. Morand [t], S. Morganti [p], V. Morgunov [m], R. Mount [κ], E. Nagy [u, a], M. Napolitano [e], H. Newman [κ], M.A. Niaz [g], L. Niessen [v], W.D. Nowak [θ], H. Nowak [θ], S. Nowak [θ], D. Pandoulas [v], G. Paternoster [e], S. Patricelli [e], Y.J. Pei [v], D. Perret-Gallix [t], J. Perrier [s], A. Pevsner [d], M. Pieri [b], P.A. Piroué [q], V. Plyaskin [m], M. Pohl [h], V. Pojidaev [m], N. Produit [s], J.M. Qian [i, g], K.N. Qureshi [g], R. Raghavan [o], G. Rahal-Callot [h], P. Razis [h], K. Read [q], D. Ren [h], Z. Ren [g], S. Reucroft [f], T. Riemann [θ], C. Rippich [α], H.A. Rizvi [g], B.P. Roe [n], M. Röhner [v], S. Röhner [v], Th. Rombach [v], L. Romero [c], J. Rose [v], S. Rosier-Lees [t], R. Rosmalen [w], Ph. Rosselet [y], J.A. Rubio [a, c], W. Ruckstuhl [s], H. Rykaczewski [h], M. Sachwitz [θ], J. Salicio [c], J.M. Salicio [c], G. Sartorelli [ℓ, g], G. Sauvage [t], A. Savin [m], V. Schegelsky [j], D. Schmitz [v], P. Schmitz [v], M. Schneegans [t], M. Schöntag [v], H. Schopper [ξ], D.J. Schotanus [w], H.J. Schreiber [θ], R. Schulte [v], S. Schulte [v], K. Schultze [v], J. Schütte [μ], J. Schwenke [v], G. Schwering [v], C. Sciacca [e], R. Sehgal [g], P.G. Seiler [h], J.C. Sens [w], I. Sheer [z], V. Shevchenko [m], S. Shevchenko [m], X.R. Shi [α], K. Shmakov [m], V. Shoutko [m], E. Shumilov [m], N. Smirnov [j], A. Sopczak [κ, z], C. Souyri [t], C. Spartiotis [d], T. Spickermann [v], B. Spiess [x], P. Spillantini [b], R. Starosta [v], M. Steuer [ℓ, i], D.P. Stickland [q], B. Stöhr [h], H. Stone [s], K. Strauch [μ], B.C. Stringfellow [γ], K. Sudhakar [o, v], G. Sultanov [a], R.L. Sumner [q], H. Suter [h], R.B. Sutton [α], J.D. Swain [g], A.A. Syed [g], X.W. Tang [ζ], E. Tarkovsky [m], J.M. Thenard [t], E. Thomas [g], C. Timmermans [w], Samuel C.C. Ting [i], S.M. Ting [i], Y.P. Tong [ε], F. Tonisch [θ], M. Tonutti [v], S.C. Tonwar [o], J. Tòth [u], G. Trowitzsch [θ], K.L. Tung [ζ], J. Ulbricht [x], L. Urbàn [u], U. Uwer [v], E. Valente [p], R.T. Van de Walle [w], H. van der Graaf [w], I. Vetlitsky [m], G. Viertel [h], P. Vikas [g], U. Vikas [g], M. Vivargent [t, i], H. Vogel [α], H. Vogt [θ], M. Vollmar [v], G. Von Dardel [a], I. Vorobiev [m], A.A. Vorobyov [j], An.A. Vorobyov [j], L. Vuilleumier [y], M. Wadhwa [g], W. Walk [a], W. Wallraff [v], C.R. Wang [η], G.H. Wang [α], J.H. Wang [ζ], Q.F. Wang [μ], X.L. Wang [η], Y.F. Wang [b], Z. Wang [g], Z.M. Wang [g, η], J. Weber [h], R. Weill [y], T.J. Wenaus [i], J. Wenninger [s], M. White [i], R. Wilhelm [w], C. Willmott [c], F. Wittgenstein [a], D. Wright [q], R.J. Wu [ζ], S.L. Wu [g], S.X. Wu [g], Y.G. Wu [ζ], B. Wysłouch [i, a], Z.Z. Xu [η], Z.L. Xue [λ], D.S. Yan [λ], B.Z. Yang [η], C.G. Yang [ζ], G. Yang [g], K.S. Yang [ζ], Q.Y. Yang [ζ], Z.Q. Yang [λ], Q. Ye [g], C.H. Ye [g], S.C. Yeh [ε], Z.W. Yin [λ], J.M. You [g], C. Zabounidis [f], C. Zaccardelli [κ], L. Zehnder [h], M. Zeng [g], Y. Zeng [v], D. Zhang [z], D.H. Zhang [w], S.Y. Zhang [ζ], Z.P. Zhang [η], J.F. Zhou [v], R.Y. Zhu [κ], A. Zichichi [a, g] and J. Zoll [a]

[a] *European Laboratory for Particle Physics, CERN, CH-1211 Geneva 23, Switzerland*
[b] *INFN – Sezione di Firenze and University of Firenze, I-50125 Florence, Italy*
[c] *Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas, CIEMAT, E-28040 Madrid, Spain*
[d] *Johns Hopkins University, Baltimore, MD 21218, USA*
[e] *INFN – Sezione di Napoli and University of Naples, I-80125 Naples, Italy*
[f] *Northeastern University, Boston, MA 02115, USA*
[g] *World Laboratory, FBLJA Project, CH-1211 Geneva, Switzerland*
[h] *Eidgenössische Technische Hochschule, ETH Zürich, CH-8093 Zurich, Switzerland*
[i] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[j] *Leningrad Nuclear Physics Institute, SU-188 350 Gatchina, USSR*
[k] *Central Laboratory of Automation and Instrumentation, CLANP, Sofia, Bulgaria*
[ℓ] *INFN – Sezione di Bologna, I-40126 Bologna, Italy*
[m] *Institute of Theoretical and Experimental Physics, ITEP, SU-117 259 Moscow, USSR*
[n] *University of Michigan, Ann Arbor, MI 48109, USA*
[o] *Tata Institute of Fundamental Research, Bombay 400 005, India*
[p] *INFN – Sezione di Roma and University of Rome "La Sapienza", I-00185 Rome, Italy*
[q] *Princeton University, Princeton, NJ 08544, USA*
[r] *Union College, Schenectady, NY 12308, USA*
[s] *University of Geneva, CH-1211 Geneva 4, Switzerland*

[ι] *Laboratoire de Physique des Particules, LAPP, F-74519 Annecy-le-Vieux, France*
[υ] *Central Research Institute for Physics of the Hungarian Academy of Sciences, H-1525 Budapest 114, Hungary*
[ν] *I. Physikalisches Institut, RWTH, D-5100 Aachen, FRG* [1]
and III. Physikalisches Institut, RWTH, D-5100 Aachen, FRG [1]
[w] *National Institute for High Energy Physics, NIKHEF, NL-1009 DB Amsterdam, The Netherlands*
and NIKHEF-H and University of Nijmegen, NL-6525 ED Nijmegen, The Netherlands
[x] *Paul Scherrer Institut (PSI), Würenlingen, Switzerland*
[y] *University of Lausanne, CH-1015 Lausanne, Switzerland*
[z] *University of California, San Diego, CA 92182, USA*
[α] *Carnegie Mellon University, Pittsburgh, PA 15213, USA*
[β] *Institut de Physique Nucléaire de Lyon, IN2P3-CNRS/Université Claude Bernard, F-69622 Villeurbanne Cedex, France*
[γ] *Purdue University, West Lafayette, IN 47907, USA*
[δ] *University of Alabama, Tuscaloosa, AL 35486, USA*
[ε] *High Energy Physics Group, Taiwan, ROC*
[ζ] *Institute of High Energy Physics, IHEP, Beijing, PRC*
[η] *Chinese University of Science and Technology, USTC, Hefei, Anhui 230 029, PRC*
[θ] *High Energy Physics Institute, DDR-1615 Zeuthen-Berlin, GDR*
[κ] *California Institute of Technology, Pasadena, CA 91125, USA*
[λ] *Shanghai Institute of Ceramics, SIC, Shanghai, PRC*
[μ] *Harvard University, Cambridge, MA 02139, USA*
[ξ] *University of Hamburg, D-2000 Hamburg, FRG*

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We have measured the partial width and forward–backward charge asymmetry for the reaction $e^+e^- \to Z^0 \to \mu^+\mu^-(\gamma)$. We obtain a partial width $\Gamma_{\mu\mu}$ of $83.3 \pm 1.3(\text{stat}) \pm 0.9(\text{sys})$ MeV and the following values for the vector and axial vector couplings: $g_V = -0.062^{+0.020}_{-0.015}$ and $g_A = -0.497^{+0.005}_{-0.005}$. From our measurement of the partial width and the mass of the Z^0 boson we determine the effective electroweak mixing angle, $\sin^2\bar{\theta}_w = 0.232 \pm 0.005$, and the neutral current coupling strength parameter, $\rho = 0.998 \pm 0.016$.

1. Introduction

Purely leptonic reactions have been used extensively to study electroweak effects and to test the standard model [1]. It is advantageous to use leptonic channels since they can be calculated precisely in higher order perturbation theory, and experimentally leptons can be clearly identified and measured with high precision. In this paper we present a new measurement of the cross section and the forward–backward charge asymmetry in the process $e^+e^- \to Z^0 \to \mu^+\mu^-(\gamma)$ at energies near the Z^0 resonance with a four-fold increase in statistics over our earlier measurements [2]. Other measurements of the $e^+e^- \to \mu^+\mu^-(\gamma)$ reactions have been reported by experiments at LEP [3,4].

We use our measurements to determine the vector and axial vector couplings of the Z^0, g_V, and g_A, to muons, the effective weak mixing angle $\sin^2\bar{\theta}_w$ and the neutral current coupling strength parameter ρ.

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2. Detector and data collection

The L3 detector has been described in detail elsewhere [5]. It consists of a central tracking chamber, a BGO electromagnetic calorimeter, a plastic scintillator hodoscope, a uranium-proportional chamber hadron calorimeter, and a high precision muon spectrometer inside a 0.5 T solenoidal magnet. Forward BGO arrays, on either side of the detector, measure the luminosity by detecting small angle Bhabha events.

The $\mu^+\mu^-(\gamma)$ data sample is composed of data collected during the periods October–December 1989 and March–June 1990. For this analysis a new determination of the 1989 luminosity was performed; the complete details of which are described in ref. [6].

Systematic errors of 1.7% and 1.3% have been assigned to the luminosity measurements of the 1989 and 1990 data samples respectively.

The primary trigger for $\mu^+\mu^-(\gamma)$ events requires at least one track in the muon chambers and one scintillator hit. The trigger efficiency has been studied by using an independent trigger that requires at least two tracks in the central tracking chamber. We find that the combined trigger efficiency for $\mu^+\mu^-(\gamma)$ events is greater than 99.9%.

3. Event selection

The selection of $Z^0 \to \mu^+\mu^-(\gamma)$ events is based on information from the muon chambers; electromagnetic and hadronic calorimeters; and the scintillation counters. The selection criteria are as follows:

(1) The event is required to contain two tracks in the muon chambers each of which has a reconstructed momentum greater than 2.0 GeV.

(2) At least one of the muons must have a transverse distance of closest approach to the interaction point less than 100 mm and at least one must have longitudinal distance of closest approach less than 100 mm.

(3) Each muon track has to be associated with a scintillator hit and the time of the hit relative to the bunch crossing must be consistent with a particle produced at the interaction point. The measured time after correcting for the time of flight must be less than 3.0 ns. Cosmic rays are removed from the sample by requiring that the time difference, between the counters associated with each muon, be less than 3.5 ns. The time resolution of the scintillation counters has been measured to be 0.5 ns.

(4) Hadronic events are removed from the sample by requiring that the event contain less than 15 calorimetric clusters.

(5) $e^+e^- \to e^+e^-\mu^+\mu^-$ and $Z^0 \to \tau^+\tau^- \to \mu^+\mu^- + \nu$'s events are removed by requiring that the sum of the muon momenta be greater than $0.5\sqrt{s}$.

After rejecting runs which might bias the cross section because of detector faults, 1836 events, corresponding to an integrated luminosity of 3.0 pb^{-1}, survive the above selection requirements and are used in our determination of the cross section and partial width.

For the measurement of the charge asymmetry the following additional cuts are applied:

(6) The muons are required to have opposite charge so that the event can be unambiguously classified as forward or backward.

(7) Both muons must satisfy $|\cos\theta| < 0.8$; where θ is the angle of the muon with respect to the beam.

(8) The acollinearity angle, 180° minus the angle between the muons, must be less than 15°.

Using all runs, 1880 events, corresponding to an integrated luminosity of 3.2 pb^{-1}, survive the above selection requirements and are used in our determination of the forward–backward charge asymmetry. By varying the cuts, we estimate that the systematic uncertainty in the event selection is 0.7%.

To determine the acceptance, $e^+e^- \to \mu^+\mu^-(\gamma)$ events were generated using a Monte Carlo program [7]. The response of the L3 detector for these events is simulated with a program [8] which includes energy loss, multiple scattering, and electromagnetic and nuclear interactions in detector components. The simulated events are reconstructed in a manner analogous to real data. The acceptance has been determined as a function of $\sqrt{s}$. At $\sqrt{s} \approx M_Z$ the acceptance, for cuts 1–5, is 58.5%, it varies by 2.7% within the energy range $M_Z \pm 3$ GeV. We have assigned a systematic error of 1.2% to our acceptance. This includes a 0.6% statistical uncertainty and a 1.0% uncertainty due to detector and reconstruction efficiency.

We estimate a background from $Z^0 \to \tau^+\tau^- \to \mu^+\mu^- + \nu$'s events of 0.5%. Other sources of background (cosmic rays, $e^+e^- \to e^+e^- - \mu^+\mu^-$, hadronic events, etc.) are negligible.

Higher order radiative corrections account for significant deviations from first order predictions in the regions of the Z^0 pole. For example the charge asymmetry at $\sqrt{s} = M_Z + 3$ GeV is reduced by $\sim 50\%$ due to hard, initial and final state, photon bremsstrahlung. Thus a good understanding of photon radiation is essential for precise measurements of electroweak parameters. We have measured these radiative processes directly by studying $\mu^+\mu^-\gamma$ events. For each event the largest electromagnetic cluster in the BGO calorimeter is identified as the photon. Fig. 1a shows the measured photon spectrum for $E_\gamma > 0.5$ GeV. The effect of photon radiation can also be seen in fig. 1b, where the acollinearity angle of the $\mu^+\mu^-$ pair is

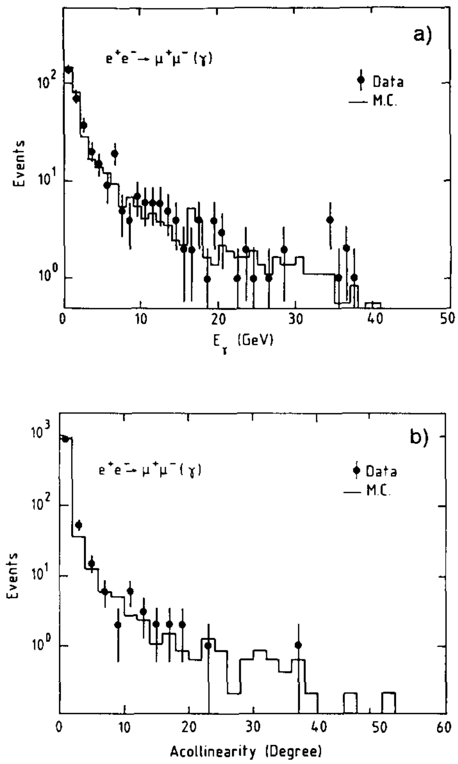

Fig. 1. (a) Photon energy spectrum for $\mu^+\mu^-(\gamma)$ events. (b) Acollinearity distribution for $\mu^+\mu^-(\gamma)$ events ($\sqrt{s} \approx M_Z$).

shown. In both cases the Monte Carlo correctly simulates the effects of hard photon radiation.

4. Partial width for $Z^0 \to \mu^+\mu^-(\gamma)$

We determine the cross section for the reaction $e^+e^- \to \mu^+\mu^-(\gamma)$ as a function of $\sqrt{s}$ in the energy region of the Z^0 resonance. The results obtained from the 1990 data are summarized in table 1. Using these measurements and the measurements from 1989 [2] we fit M_Z and Γ_Z using an analytical form [9] for the Z^0 cross section. We obtain $M_Z = 91.08 \pm 0.07$ GeV and $\Gamma_Z = 2.45 \pm 0.15$ GeV, in excellent agreement with our measurements derived from the hadronic channel [4,6], $M_Z = 91.164 \pm 0.033$ GeV and $\Gamma_Z = 2.494 \pm 0.025$ GeV.

To determine the muonic partial width, we constrain the mass and width of the Z^0 to the values obtained from the hadronic channel. The measured

Table 1
Number of events and cross section for $e^+e^- \to \mu^+\mu^+\mu^-(\gamma)$.

$\sqrt{s}$ (GeV)	Number of $\mu^+\mu^-(\gamma)$ events	$\sigma_{\mu^+\mu^-}$ (nb)
88.220	16	0.26 ± 0.07
89.219	44	0.39 ± 0.06
90.219	135	1.00 ± 0.09
91.218	1003	1.44 ± 0.05
92.217	89	1.05 ± 0.11
93.217	42	0.44 ± 0.07
94.216	23	0.41 ± 0.08

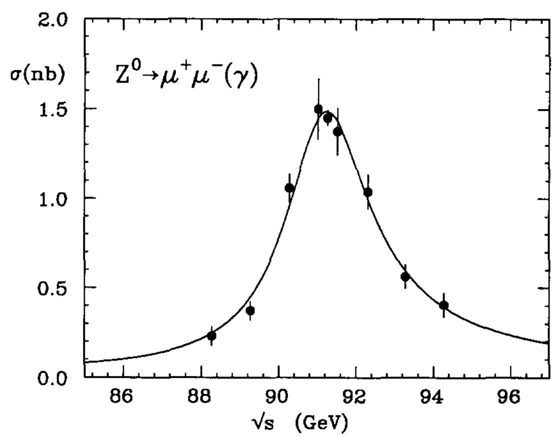

Fig. 2. Measured cross sections, as a function of $\sqrt{s}$, for the reaction $e^+e^- \to \mu^+\mu^-$. Neighboring energy points have been combined. The curve is a fit to the data to obtain $\Gamma^{\mu}_{\ell\ell}$ as described in the text.

$e^+e^- \to \mu^+\mu^-(\gamma)$ cross sections are displayed in fig. 2 together with the result of the fit. We obtain a fit with $\chi^2 = 15.5$ for 15 degrees of freedom. We find

$$\Gamma^{\mu}_{\ell\ell} \equiv \sqrt{\Gamma_{ee}\Gamma_{\mu\mu}} = 83.3 \pm 1.3(\text{stat}) \pm 0.9(\text{sys}) \text{ MeV}.$$

The statistical error includes a 0.9 MeV contribution from the statistical error in our measured value of Γ_Z.

Assuming lepton universality, $\Gamma^{\mu}_{\ell\ell}$ can be expressed in terms of an effective electroweak mixing angle $\sin^2\bar{\theta}_W$ and the coupling strength parameter ρ [10]:

$$\Gamma^{\mu}_{\ell\ell} = \rho \frac{G_F M_Z^3}{24\pi\sqrt{2}} [1 + (1 - 4\sin^2\bar{\theta}_w)^2] .$$

From the relation

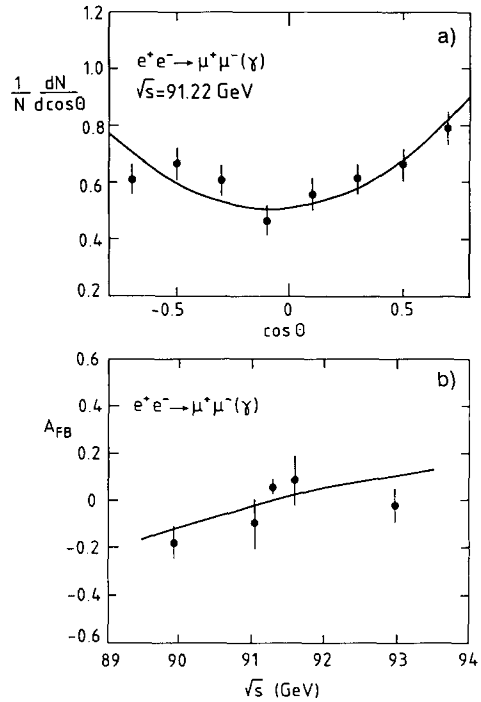

Fig. 3. (a) Acceptance corrected $\cos\theta$ distribution for μ^- in $\mu^+\mu^-(\gamma)$ events at $\sqrt{s}\approx M_Z$; where θ is the angle between the incoming e^- and the outgoing μ^-. The curve is a fit to the data. (b) Measured forward–backward charge asymmetry, A_{FB}, as a function of $\sqrt{s}$ for the reaction $e^+e^-\to\mu^+\mu^-$; neighboring energy points have been grouped together. The curve is the prediction of the standard model as described in the text.

$$\rho M_Z^2 \sin^2\bar{\theta}_w \cos^2\bar{\theta}_w = \frac{\pi\alpha(M_Z)}{\sqrt{2}\,G_F}$$

and our measured values for M_Z and $\Gamma_{\ell\ell}^{\mu}$ we obtain

$$\sin^2\bar{\theta}_W = 0.232 \pm 0.005, \quad \rho = 0.998 \pm 0.0016 .$$

5. Forward–backward charge asymmetry

The measured angular distribution, corrected for acceptance, near the Z^0 resonance, at $\sqrt{s}\approx 91.22$ GeV, is shown in fig. 3a. The forward–backward charge asymmetry is defined as

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

We determine the asymmetry from a fit to the acceptance corrected $d\sigma/d\cos\theta$ angular distribution using the function form $f(\theta) = a(1+\cos^2\theta) + b\cos\theta$; where θ is the angle between the incoming e^- and the outgoing μ^-. The solid line in fig. 3a represents the result of the fit, corresponding to $A_{FB} = 0.054 \pm 0.026$, for the angular range $|\cos\theta| < 0.8$.

Results from the 1990 data sample, after extrapolation to the full angular range, are presented in table 2. Fig. 3b shows the measured asymmetries of the combined 1989 and 1990 data samples as a function of $\sqrt{s}$; neighboring energy points have been grouped together. The curve represents the prediction of the standard model for our cuts, assuming $M_{top} = 150$ GeV and $M_H = 100$ GeV.

Using the relation

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

we find

$$g_A^2 + g_V^2 = 0.251 \pm 0.005 .$$

For a precise determination of g_V and g_A we perform a fit of the asymmetries including interference, initial and final state radiative corrections with soft photon exponentiation [11]. Assuming lepton universality we fit the effective vector and axial vector couplings as model independent parameters [12]. We have used the data summarized in table 2 and earlier asymmetry results [2] in the fit. Using the Z^0 mass and Γ_Z determined with our hadronic data [6] and the above relationship we obtain (including systematics)

$$g_A = -0.497^{+0.005}_{-0.005},$$

$$g_V = -0.062^{+0.020}_{-0.015}$$

with a χ^2 of 13.5 for 11 degrees of freedom. The signs

Table 2
Forward–backward charge asymmetry for $e^+e^-\to\mu^+\mu^-(\gamma)$.

$\sqrt{s}$ (GeV)	A_{FB} (%)
88.22	−33 ± 29
89.22	17 ± 18
90.22	−20.5 ± 9.3
91.22	4.7 ± 3.2
92.22	−4.6 ± 11
93.22	10 ± 16
94.22	17 ± 22

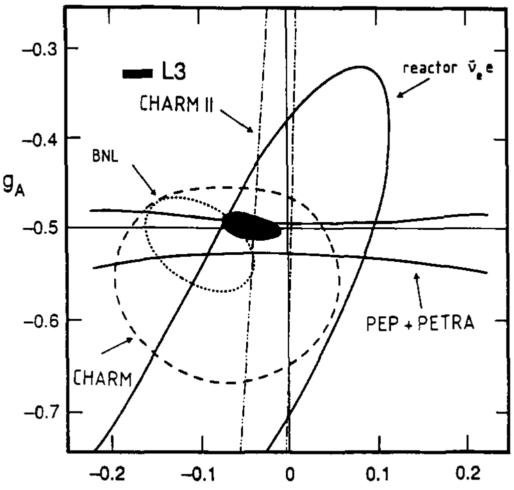

Fig. 4. g_V and g_A results obtained from neutrino experiments: CHARM [13], BNL [14], CHARM II [15]; reactor $\bar{\nu}_e$ e [18] experiments; and low energy e^+e^- experiments: PEP+PETRA [17] expressed as contours. The shaded area represents the L3 measurement. All contours shown are at the 68% confidence level except for the PEP+PETRA curve which is at a confidence level of 95%.

of g_V and g_A have been inferred from results of other experiments [13–16]. Fig. 4 [#1] compares our determination of g_A and g_V to previous measurements in neutrino interactions and at PETRA and PEP [13–18].

6. Conclusion

We have measured $\Gamma^{\mu}_{\ell\ell}$ to be $83.3 \pm 1.3(\mathrm{stat}) \pm 0.9(\mathrm{sys})$ MeV. We have also measured the forward–backward charge asymmetry in $\mu^+\mu^-(\gamma)$ production as a function of $\sqrt{s}$. This allows us to determine the vector and axial vector couplings of the muon to the Z^0: $g_V = -0.062^{+0.020}_{-0.015}$ and $g_A = -0.497^{+0.005}_{-0.005}$. From our measurement of the partial width in $Z^0 \to \mu^+\mu^-(\gamma)$ and the mass of the Z^0 boson we determine the effective electroweak mixing angle $\sin^2\bar{\theta}_W = 0.232 \pm 0.005$ and the coupling strength parameter $\rho = 0.998 \pm 0.016$. All results are consistent with standard model predictions.

[#1] Note in fig. 4, that in order to compare with our result, we have plotted the result of ref. [14] by adding in quadrature their statistical and systematic errors.

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