

Precision Measurement of Electroweak Effects in $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s} = 29$ GeV

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A high-statistics measurement has been made of the process $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s} = 29$ GeV with the MAC detector at the SLAC storage ring PEP. The electroweak forward-backward charge asymmetry for a sample of approximately 16000 events was measured to be $A_{\mu\mu} = -0.063 \pm 0.008 \pm 0.002$. The ratio of the cross section to the lowest-order QED cross section was measured to be $R_{\mu\mu} = 1.01 \pm 0.01 \pm 0.03$. From these results the weak neutral axial-vector and vector couplings are determined to be $g_A^e g_A^\mu = 0.25 \pm 0.03 \pm 0.01$ and $g_V^e g_V^\mu = -0.02 \pm 0.03 \pm 0.09$.

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The process $e^+e^- \rightarrow \mu^+\mu^-$ provides a low-background test of the theory of electroweak interactions.¹ The axial-vector part of the weak neutral current causes a forward-backward asymmetry in the angular distribution, while the vector part produces a very small change in the cross section relative to the pure QED prediction. Previously published measurements of this process by Fernandez *et al.*² and other groups on the storage rings PEP^{3,4} at SLAC and PETRA⁵⁻⁹ at DESY have been based on just a few thousand events. The MAC-detector results reported here are based on a total integrated luminosity of 222 ± 4 pb⁻¹ at a c.m. energy of 29 GeV, yielding approximately 16000 events with reduced backgrounds due to improved selection criteria.

The MAC detector¹⁰ features very large solid-angle coverage (> 95% of 4π) with both electromagnetic and hadronic calorimetry and tracking of charged particles. A ten-layer central drift chamber (CD) in a 0.57-T axial magnetic field provides momentum resolution of $\sigma_p/p^2 = 0.065 \sin\theta$. This chamber is surrounded by a hexagonal barrel of lead-plate electromagnetic calorimeters and iron-plate hadronic calorimeters, closed by iron-plate end caps, all with proportional-chamber sampling. The approximately 1-m thickness of central and end-cap absorber iron is magnetized toroidally to 1.7 T and is surrounded by three to six layers of drift chambers which track emerging charged particles with a momentum resolu-

tion of $\sigma_p/p \approx 0.3$. Scintillators placed inside the central and end-cap iron provide trigger and time-of-flight information.

Substantial trigger redundancy for this measurement is provided by two independent event triggers, either (a) a coincidence of opposing scintillators, or (b) at least one penetrating track defined by hits in the CD in coincidence with appropriate signals in the corresponding scintillator and hadron calorimeter. To be accepted as μ pairs, triggered events must satisfy the following conditions: (1) Two CD tracks must form a vertex at the beam intersection region, be collinear within 15°, and satisfy $|\cos\theta| < 0.95$. (2) Each of the tracks must deposit energy in the electromagnetic calorimeter consistent with minimum ionization, and have a scintillator hit with time of flight consistent with the track's originating at the beam interaction point. (3) At least one of the two CD tracks must have a corresponding track in the outer drift-chamber system and a momentum of at least 7.0 GeV determined from the weighted average of the separate measurements in the two systems. (4) The charge assignments by the CD and the outer drift-chamber system (if present) must agree for each track, and the two tracks must have opposite charge.

A total of 16058 events passed all of these cuts. The selection criteria are designed to reject events from Bhabha scattering, cosmic rays, two-photon processes ($ee\mu\mu$ final states), and tau pairs. Of these

possible backgrounds, Bhabha scattering is of most concern since the reaction exhibits almost 100% charge asymmetry. However, from a study of the effect of the cuts on a large sample of Bhabha events in the MAC detector, we find that the contamination in the μ -pair sample is less than 0.05%. Cosmic rays passing the scintillator-timing and vertex-position cuts are found to contribute less than 0.5%. Monte Carlo calculations have been made of the background from two-photon μ pairs¹¹ and τ pairs,¹² including a full detector simulation¹³ with all the conditions applied to the data. The contributions to the μ -pair sample are determined to be $(0.4 \pm 0.05)\%$ from two-photon μ pairs and $(0.9 \pm 0.1)\%$ from τ pairs. Both background contributions have been subtracted from the data. All of the above backgrounds introduce an uncertainty of less than 0.001 in the asymmetry and 0.7% in the total cross section.

The detection efficiency for μ pairs was calculated by a Monte Carlo simulation and was checked by use of the redundancy in the trigger. The overall geometrical and detector efficiency is 67%. Asymmetric biases in the detector efficiency are found to be very small and tend to cancel because of periodic reversal of the magnetic fields. The overall charge misidentification probability is determined to be 0.2%, dominated by the 25% of the events with only one matching track in the outer drift-chamber system.

The cross section for $e^+e^- \rightarrow \mu^+\mu^-$ is given in the Born approximation by

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s} R_{\mu\mu} (1 + \cos^2\theta + \frac{8}{3} A_{\mu\mu} \cos\theta), \quad (1)$$

where θ is the angle between the scattered μ^+ and the incident e^+ . $R_{\mu\mu}$ denotes the ratio of the total μ -pair cross section to the lowest-order QED cross section, and is given by

$$R_{\mu\mu} = 1 + 2g_V^e g_V^\mu \text{Re}\chi + (g_V^{e2} + g_A^{e2})(g_V^{\mu2} + g_A^{\mu2})|\chi|^2, \quad (2)$$

where g_V^e and g_A^e are the vector and axial-vector electroweak couplings of the electron and muon, respectively. The parameter $A_{\mu\mu}$ in (1) is given by

$$A_{\mu\mu} = (\frac{3}{2} g_A^e g_A^\mu \text{Re}\chi + 3g_V^e g_V^\mu g_A^e g_A^\mu |\chi|^2) / R_{\mu\mu}, \quad (3)$$

and corresponds to the forward-backward charge asymmetry for the full solid angle. The quantity χ is given by

$$\chi = \frac{s}{4 \sin^2\theta_W \cos^2\theta_W (1 - \Delta) [(s - M_Z^2) + iM_Z\Gamma_Z]}, \quad (4)$$

where θ_W is the mixing angle (Weinberg angle) and $\Delta = 0.070$ is the self-energy correction to the Z^0 propa-

gator.¹⁴ With $\sin^2\theta_W = 0.22$, $M_Z = 93 \text{ GeV}/c^2$, and the standard-model values of $g_A^e g_A^\mu = 0.25$ and $g_V^e g_V^\mu = 0.25 \times (1 - 4 \sin^2\theta_W)^2 = 0.0036$, the predicted asymmetry is $A_{\mu\mu} = -0.063$ and the predicted ratio is $R_{\mu\mu} = 1.001$.

The raw data of this experiment were corrected for the backgrounds previously described and for radiative effects in both the γ and Z^0 exchange diagrams. A Monte Carlo calculation¹² with detector simulation predicts radiative corrections to the charge asymmetry of $+0.0314 \pm 0.0006$, 20% of which is due to photonic corrections to the Z^0 exchange diagrams. The ability of the Monte Carlo procedure to model the data is checked by comparisons to the observed differential cross section for radiative muon-pair production.^{2,15} The angular dependence of the corrected data is shown in Fig. 1(a), with the dotted line representing a $(1 + \cos^2\theta)$ distribution. The data with the QED contributions subtracted out, shown in Fig. 1(b), clearly demonstrate the expected linear dependence on $\cos\theta$. A two-parameter fit to the data was made to determine the charge asymmetry $A_{\mu\mu}$ and the cross-section ratio $R_{\mu\mu}$. The integrated luminosity represented by the sample was determined from Bhabha-scattering events. The full statistical and systematic errors of the background subtraction were included. The fit, shown by the solid curve in Fig. 1(a), has $\chi^2 = 14.6$ for 18 de-

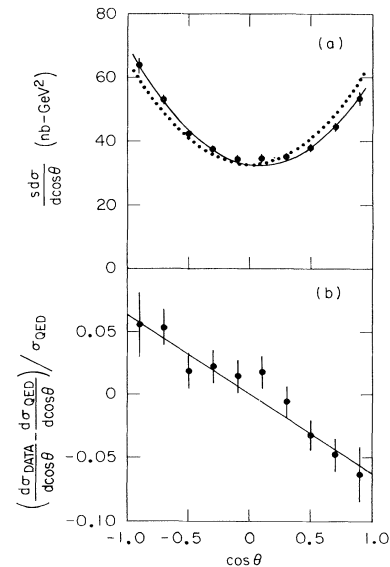


FIG. 1. (a) Angular dependence of the cross section for the process $e^+e^- \rightarrow \mu^+\mu^-$. The data are shown after corrections (see text), together with the results of a two-parameter fit by Eq. (1) (solid line). The dotted line shows the expected lowest-order QED cross section. (b) The difference between the measured muon-pair cross section and the QED cross section divided by the total QED cross section, both to order α^2 . The electroweak prediction corresponding to $A_{\mu\mu} = -0.063$ is shown as the solid line.

degrees of freedom and yields

$$A_{\mu\mu} = -0.063 \pm 0.008 \pm 0.002,$$

$$R_{\mu\mu} = 1.01 \pm 0.01 \pm 0.03,$$

where the first error is statistical and the second represents the systematic error. These values are in excellent agreement with the standard-model predictions. The error in the asymmetry is a factor of 2 smaller than in previously published measurements by this and other groups.²⁻⁹ The precision of the $R_{\mu\mu}$ measurement is limited by systematic uncertainties in the detection efficiency and in the determination of the integrated luminosity. Several authors prefer that the Z^0 self-energy not be included in the Born approximation. If this correction is not included in Eq. (4) ($\Delta=0.0$) and the data are corrected for the self-energy, then both the expected and measured charge asymmetries are -0.059 .

The measured $A_{\mu\mu}$ and $R_{\mu\mu}$ may be used to determine the parameters of the standard model. With use of the standard-model values of g_V and g_A , the 68%- and 95%-confidence-level contours in the M_Z and $\sin^2\theta_W$ plane were calculated. Figure 2 shows these contours, the best-fit value, and the determination of these quantities by Arnison *et al.* and Bagnaia *et al.* at the CERN SPS collider.¹⁶ A determination of the Z mass can be made if $\sin^2\theta_W$ is fixed to 0.22, giving $M_Z = 94^{+6}_{-6}$ GeV/ c^2 . Conversely, if M_Z is fixed at 93 GeV/ c^2 , then $\sin^2\theta_W = 0.22 \pm^{0.05}_{0.04}$.

A second interpretation of these results is obtained if the weak couplings are allowed to vary, with constant values of $\sin^2\theta_W = 0.22$ and $M_Z = 93$ GeV/ c^2 ,

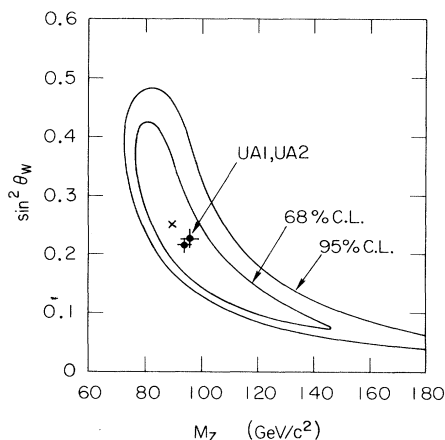


FIG. 2. Contours of allowed $\sin^2\theta_W$ and M_Z from this experiment. Both the 68%- and 95%-confidence-level limits are shown. The shapes of the contours are highly sensitive to the overall $R_{\mu\mu}$ normalization. The best-fit value and the values measured by the UA1 and UA2 experiments (Ref. 16) are also shown.

giving

$$g_A^e g_A^\mu = 0.25 \pm 0.03 \pm 0.01,$$

$$g_V^e g_V^\mu = -0.02 \pm 0.03 \pm 0.09,$$

in good agreement with theory and other published data.²⁻⁹

A test of universality for the neutral-current couplings may be made by comparison of the results of this experiment with the recent MAC-detector measurement of the tau asymmetry, $A_{\tau\tau} = -0.061 \pm 0.012 \pm 0.005$.¹⁷ The ratio of the axial-vector couplings is $g_A^\tau/g_A^\mu = 0.97 \pm 0.25$. This universality test, which involves neutral-current couplings, is in principle distinct from the universality test given by comparison of the tau and muon lifetimes, which involves charged-current couplings.

In conclusion, the differential cross section for $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s} = 29$ GeV has been measured with a much improved precision compared to previous experiments. The values calculated for $\sin^2\theta_W$ and M_Z agree well with those determined by $p\bar{p}$ collider and neutrino scattering experiments. Measurements of the electroweak couplings are found to be in excellent agreement with the standard electroweak theory.

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