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Brief Reports

New results on the reaction $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s} = 29$ GeV

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We have measured the process $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s} = 29$ GeV using the High Resolution Spectrometer at SLAC PEP. The forward-backward charge asymmetry is $A_{\mu\mu} = -(4.9 \pm 1.5 \pm 0.5)\%$ based on 5057 events. A subsample of 3488 $\mu^+\mu^-$ events in the angular range $|\cos\theta| < 0.55$ gives a cross-section ratio of $R_{\mu\mu} = 0.990 \pm 0.017 \pm 0.030$. The resulting couplings of the weak neutral current are $g_a^e g_a^\mu = 0.208 \pm 0.064 \pm 0.021$ and $g_v^e g_v^\mu = 0.027 \pm 0.051 \pm 0.089$. The QED cutoff parameters are $\Lambda_+ > 170$ GeV and $\Lambda_- > 146$ GeV at 95% C.L.

The Glashow-Salam-Weinberg standard model of electromagnetic and weak interactions[1] provides a precise description of leptonic processes. Electron-positron collisions are an ideal laboratory to study electroweak effects in a low background environment. Measurements of the process $e^+e^- \rightarrow \mu^+\mu^-$ have been reported by the various groups at SLAC PEP (Refs. 2–4) and DESY PETRA (Ref. 5). We have previously[2] reported results based on an integrated luminosity of 19.6 pb^{-1}, and in this paper we report new measurements at $\sqrt{s} = 29$ GeV using an additional sample of 86.0 pb^{-1} obtained with the High Resolution Spectrometer (HRS) at PEP.

The HRS detector is a solenoidal spectrometer which measures charged particles and electromagnetic energy over 90% of the solid angle. For the new data, a set of Cherenkov counters was located between the central and outer drift chambers.[6] The tracking system in the 16.2-kG magnetic field measures the momentum of a large-angle, 14.5-GeV/c particle to $\sim 3\%$. The charge is unambiguously identified for $|\cos\theta| < 0.9$.

A 40-module barrel shower-counter system provides electromagnetic calorimetry and time-of-flight (TOF) information over 62% of the solid angle. The energy resolution for 14.5-GeV showering particles is $\sigma_E/E = 7\%$. For minimum-ionizing particles, the energy deposition is typically 200 MeV and the time-of-flight measurement has an rms error of 360 ps. A 40-module end-cap shower-counter system provides the same information over 27% of the solid angle, but σ_E/E is $\sim 9\%$ and TOF resolution is about ± 1 ns.

Every event accepted as a $\mu^+\mu^-$ candidate had to satisfy the following conditions.

(1) It had two oppositely charged particles.

(2) Each particle had a momentum p between 7.25 and 20 GeV/c and deposited less than 1 GeV of energy E in the shower counters.

(3) Each particle was detected within 15 ns of the beam crossing time and the time difference between the two particles of an event was less than 6 ns.

(4) The distance of closest approach of a track to the vertex was less than 1 cm radially and less than 9 cm along the beam direction.

(5) The acollinearity angle was less than 25°.

These cuts effectively removed beam-gas interactions, two-photon events, and cosmic rays.

Geometrical cuts were used to avoid holes in the detector acceptance. The barrel shower-counter system covers the polar angle with uniform efficiency for $|\cos\theta| < 0.55$. The coverage of the end-cap shower-counter system used in this analysis was $0.7 < |\cos\theta| < 0.8$. The azimuthal acceptances have periodic gaps, every 9° for the barrel and every 18° for the end cap. Although the physical width of the gap is about 1 cm, a cut 3 cm wide was made. The track-finding efficiency and the trigger efficiency were measured to be uniform for $|\cos\theta| < 0.8$ using Bhabha-scattered electrons. These geometrical cuts ensured that events were accepted only within regions of the detector where the detection efficiency is uniform.

The events passing these cuts are 98.7% genuine muon pairs from the $e^+e^- \rightarrow \mu^+\mu^-$ process. The largest remaining background comes from the reaction $e^+e^- \rightarrow \tau^+\tau^-$ in which the $\tau^\pm$'s decay into muons, charged pions, and charged kaons. The fraction of such events passing the cuts was calculated to be $(0.8 \pm 0.08)\%$ of the $\mu^+\mu^-$ signal using a Monte Carlo simulation of the experiment and the known τ-decay branching ratios.

The next largest background comes from the two-photon reactions $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$, $e^+e^-\pi^+\pi^-$, $e^+e^-K^+K^-$, in which the scattered electrons are undetected at small angles with respect to the beam. From a study of the distribution of the events in fractional momentum versus acollinearity angle, we estimate this contamination to be $(0.4 \pm 0.1)\%$.

A potentially dangerous background to the charge-asymmetry measurement comes from Bhabha scattering $e^+e^- \rightarrow e^+e^-$ because the angular distribution has a steep forward peak. The Monte Carlo simulation shows that less than 0.1% of the sample in the barrel region, and 0.2% in the end-cap region, come from misidentified Bhabha-scattered electrons. The contamination from cosmic rays is $< 0.1\%$ of the signal in the barrel region and 0.3% in the end-cap region.

The resulting new data sample consists of 4246 $\mu^+\mu^-$ events, of which 3488 events were detected in the barrel-shower-counter system. The background in the latter sample was estimated to be 45 events. The reconstruction efficiency of the tracks, including the central-drift-chamber efficiency, was 99.0%. The overall efficiency, including the geometrical cuts and trigger inefficiency, was 87.4% in the barrel region.

We have studied possible asymmetric biases of the detector. The bias caused by an end-to-end azimuthal twist of the central drift chamber is negligible. The asymmetry caused by the charge misassignment is much less than 0.1% because of the high magnetic field. The symmetry of the spectrometer has been checked using hadronic annihilation events; the result is an asymmetry of $-(0.4 \pm 0.8)\%$, consistent with zero.

In order to determine the absolute cross section, we used a subsample of data in the central angular region $|\cos\theta| < 0.55$. The integrated luminosity was calculated from the Bhabha-scattered events in the same angular range. The cuts applied to obtain the Bhabha events were identical except that the energy was required to be greater than 3 GeV and E/p greater than 0.4. Since the topology of the Bhabha events and the muon events is identical, many systematic errors cancel when the ratio is taken between these two processes. The measured integrated luminosity is 86.0 ± 2.0 pb^{-1} using a simulation[7] which includes all the Feynman diagrams up to order α^3. The pure QED process alone predicts $(3477.5 \pm 17.9 \pm 104.3)$ $\mu^+\mu^-$ events in this angular range. The first error is statistical and the second systematic. The systematic uncertainty in the luminosity dominates the error. Therefore, the cross-section ratio to the QED prediction up to order α^3 is

$$R_{\mu\mu} = 0.990 \pm 0.017 \pm 0.030 \ ,$$

where the known contributions from the background processes above have been subtracted statistically.

In order to determine the forward-backward charge asymmetry, we have used the angular distribution which is shown in Fig. 1 after corrections for geometrical acceptance and the order-α^3 QED radiative correction. The overall normalization is fixed by the theoretical value of Bhabha scattering, i.e., assuming $R_{\mu\mu} = 1$. Since any binning of the data represents a loss of information, we used a maximum-likelihood-method technique to determine the asymmetry. We used

$$L(A) = \sum_{i=1}^{N} \ln[(1+\cos^2\theta_i + A\cos\theta_i)E(\cos\theta_i)R(\cos\theta_i)] \ ,$$

where A is a parameter to be determined, $E(\cos\theta_i)$ is an acceptance correction and is symmetric in $\cos\theta_i$, and $R(\cos\theta_i)$ is the radiative correction.

The charge asymmetry, $A_{\mu\mu}$ extrapolated to the full solid angle, is defined as

$$A_{\mu\mu} \equiv (N_f - N_b)/(N_f + N_b) = \tfrac{3}{8}A \ ,$$

where N_f (N_b) is the number of events with the μ^+ in the forward (backward) hemisphere with respect to the e^+ beam direction. The result is

$$A_{\mu\mu} = -(4.4 \pm 1.6 \pm 0.5)\% \ .$$

The systematic error of 0.5% includes the Bhabha-scattering background and an estimate of possible detector bias.

The curve in Fig. 1 shows the expected angular distribution with the asymmetry parameter determined above. The fit yields a $\chi^2 = 19.3$ for 25 degrees of freedom. The QED correction up to order α^3 contributes $+1.6\%$ to $A_{\mu\mu}$.

We have published[2] a value of $A_{\mu\mu} = -(8.4 \pm 4.3)\%$ based on the data sample of 19.6 pb^{-1}. The two measurements are consistent. Since there are considerable differences in the detector geometry, the trigger, and the detector configuration between two data samples, we average the measurements assuming that the error distributions are

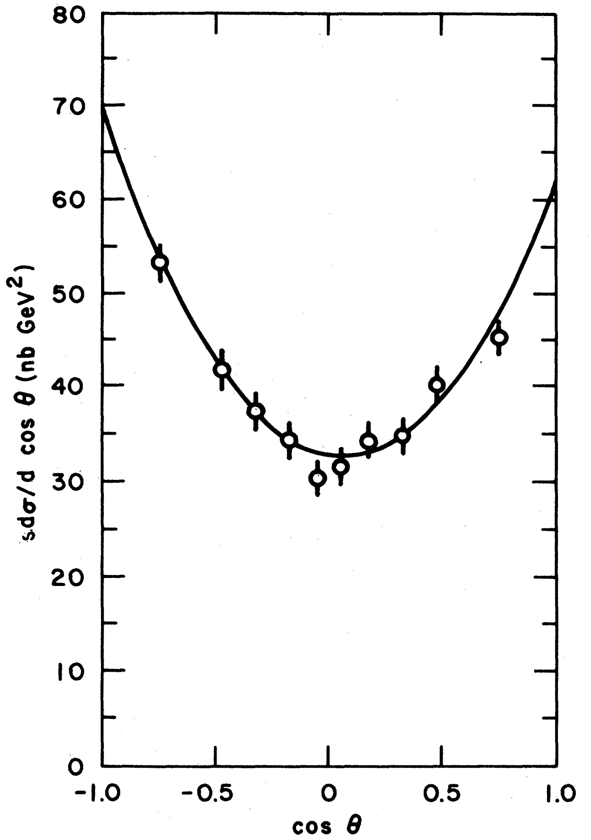

FIG. 1. The angular distribution of muons for 4246 events of the process $e^+e^- \to \mu^+\mu^-$.

Gaussian. The final result is then

$$A_{\mu\mu} = -(4.9 \pm 1.5 \pm 0.5)\%$$

based on a total of 5057 $\mu^+\mu^-$ events and a total integrated luminosity of 106 pb^{-1}.

The standard model predicts the differential cross section to be

$$d\sigma/d\cos\theta = (\pi\alpha^2/2s)[R_{\mu\mu}(1+\cos^2\theta) + A\cos\theta] \ ,$$

where

$$R_{\mu\mu} = 1 + 2g_v^e g_v^\mu \operatorname{Re}\chi, \quad A = 4g_a^e g_a^\mu \operatorname{Re}\chi \ ,$$

and

$$\chi = \frac{1}{4\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M_Z{}^2 + iM_Z\Gamma_Z} \ ,$$

with the interference terms included. The charge asymmetry is then $A_{\mu\mu} = 3A/8R_{\mu\mu}$. The standard-model values are

$$g_a^e g_a^\mu = 0.25, \quad g_v^e g_v^\mu = 0.25(1 - 4\sin^2\theta_W)^2 = 0.0036 \ ,$$

for $\sin^2\theta_W = 0.22$, where θ_W is the Weinberg angle. Taking recent values for the Weinberg angle of $\sin^2\theta_W = 0.22 \pm 0.01$ and a Z^0 mass of[8] (93 ± 2) GeV, the predicted values of $A_{\mu\mu}$ and $R_{\mu\mu}$ at $\sqrt{s} = 29$ GeV are $A_{\mu\mu} = -5.9\%$ and $R_{\mu\mu} = 1.00$. Our measurements are therefore consistent with these predictions.

TABLE I. Vector and axial-vector couplings.

	HRS only	PEP average
$g_a^e g_a^\mu$	$0.208 \pm 0.064 \pm 0.021$	0.249 ± 0.041
$g_v^e g_v^\mu$	$0.027 \pm 0.051 \pm 0.089$	0.019 ± 0.070

With the above values for $\sin^2\theta_W$ and M_Z, a model-independent determination of the vector and the axial-vector couplings from our measurements of $A_{\mu\mu}$ and $R_{\mu\mu}$ gives the results listed in Table I. Alternatively, assuming $M_Z = 93$ GeV, we find $\sin^2\theta_W = 0.29^{+0.21}_{-0.09}$ from our data. A more precise determination can be made by averaging the three PEP experiments. The Mark II collaboration[3] measures $A_{\mu\mu} = -(7.1 \pm 1.7)\%$ and $R_{\mu\mu} = 1.002 \pm 0.013 \pm 0.016$. The MAC collaboration,[4] based on about 10 000 $\mu^+\mu^-$ events, gives $A_{\mu\mu} = -(5.8 \pm 1.0 \pm 0.3)\%$ and $R_{\mu\mu} = 0.976 \pm 0.014 \pm 0.034$. The weighted averages are then

$$A_{\mu\mu} = -(5.87 \pm 0.97)\%$$

and

$$R_{\mu\mu} = 0.994 \pm 0.022 \ ,$$

where we have added the systematic and statistical errors linearly. Table I also gives the axial-vector and vector couplings calculated from these averages.

The weak radiative correction is not included in the above numbers; it could change the predicted asymmetry by about 0.3%.[7,9] The error on the axial-vector coupling is dominated by the statistics, whereas the error on the vector coupling is limited by the systematics.

Since the effect of the weak interaction on $R_{\mu\mu}$ is expected to be small, we can use our measurement of $R_{\mu\mu}$ to test QED. The QED cutoff parameters are defined by

$$\sigma_{\text{measured}} = \sigma_{\text{QED}}\left(1 \pm \frac{2s}{\Lambda_\pm{}^2}\right) \ .$$

Our data give $\Lambda_+ > 170$ GeV and $\Lambda_- > 146$ GeV at 95% C.L.

Finally, we put a limit on the additional contribution from the nonstandard models[10] such as $SU(2)_L \times SU(2)_R \times U(1)$ or $SU(2) \times U(1) \times U(1)'$, in which $g_v{}^2$ is replaced by $g_v{}^2 + 4C$. Taking $\sin^2\theta_W = 0.22 \pm 0.01$, we find $C < 0.057$ with 95% C.L.

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[1] S. L. Glashow, A. Salam, and S. Weinberg, Rev. Mod. Phys. **52**, 515 (1980).

[2] D. Bender *et al.*, Phys. Rev. D **30**, 515 (1984).

[3] N. E. Levi *et al.*, Phys. Rev. Lett. **51**, 1941 (1983).

[4] E. Fernandez *et al.*, Phys. Rev. Lett. **50**, 1238 (1983) and SLAC Pub 3133 (1983). We note that this experiment in common with all other reported measurements requires positive identification of both tracks as muons in order to classify the event as a $\mu^+\mu^-$ final state. Our experiment which does not apply this criterion has therefore somewhat different symmetric errors.

[5] W. Bartel *et al.*, Phys. Lett. **108B**, 140 (1982); B. Adeva *et al.*, Phys. Rev. Lett. **48**, 1701 (1982); H. J. Behrend *et al.*, Z. Phys. C **14**, 283 (1982); Ch. Berger *et al.*, *ibid.* **21**, 53 (1983); M. Althoff, *ibid.* **22**, 13 (1984).

[6] Signals from the Cherenkov counters were not used in this analysis. The additional multiple scattering slightly degrades the momentum resolution for the events of the second-year data compared with the first-year data.

[7] F. A. Berends and R. Kleiss, Nucl. Phys. **B177**, 237 (1981); F. A. Berends, R. Kleiss, and S. Jadach, *ibid.* **B202**, 63 (1983).

[8] G. Arnison *et al.*, Phys. Lett. **126B**, 398 (1983); P. Bagnaia, *ibid.* **129B**, 130 (1983); W. J. Marciano, in *Proceedings of the 1983 Symposium on Lepton and Photon Interactions at High Energies, Ithaca, New York,* edited by D. G. Cassel and D. L. Kreinick (Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, 1983), p. 80.

[9] R. W. Brown, K. Decker, and E. A. Paschos, Phys. Rev. Lett. **52**, 1192 (1984); M. Böhm and W. Hollik, Nucl. Phys. **B204**, 45 (1982); Z. Phys. **23**, 31 (1984).

[10] V. Barger, W. Y. Keung, and E. Ma, Phys. Rev. Lett. **44**, 1169 (1980); E. H. DeGroot *et al.*, Phys. Lett. **90B**, 427 (1980).