Measurement of $e^+e^- \rightarrow \mu^+\mu^-$: A Test of Electroweak Theories

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We use the reaction $e^+e^- \rightarrow \mu^+\mu^-$, in the Mark J detector at the DESY high-energy e^+e^- collider PETRA, to test the standard electroweak theory and find good agreement. We also set limits on the parameters of several extended gauge theories.

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The leptonic reaction

$$e^+e^- \rightarrow \mu^+\mu^- \quad (1)$$

is of particular importance for testing electroweak theories, since it is a pure s -channel reaction and the final-state particles can be well measured. The measurement of the interference effects between the electromagnetic and weak interactions at high energies determines the strength of the weak-neutral-current interaction. The (minimal) standard model is a $SU(2)_L \otimes U(1)$ gauge theory and in this interaction has two parameters, $\sin^2\theta_W$ (θ_W is the weak mixing angle), and m_{Z^0} , the mass of the neutral vector boson Z^0 . We use the measurement of reaction (1) as a test

of the standard theory¹ and we set limits on the parameters of extended gauge theories.

The Mark J detector has collected 5500 events of reaction (1) over a range of center-of-mass energies, $14 \text{ GeV} < \sqrt{s} < 46.78 \text{ GeV}$. The largest sample (3658 events) was obtained with $\langle \sqrt{s} \rangle = 34.6 \text{ GeV}$.^{2,3} (See Table I.) The measured angular distributions and details of event selection and a study of systematic effects have been discussed in Ref. 3. Other storage-ring experiments at PETRA⁴ (DESY) and PEP⁵ (SLAC) have published results on reaction (1) at somewhat lower energies.

The electroweak interaction predicts a deviation from the pointlike cross sections due to the γ - Z^0 interference,⁶

$$R_{\mu\mu} = \sigma_{\mu\mu}/\sigma_{\text{point}} = 1 - 2g_V^e g_V^\mu \chi + [(g_V^e)^2 + (g_A^e)^2][(g_V^\mu)^2 + (g_A^\mu)^2]\chi^2, \quad (2)$$

where g_V , g_A are the vector and axial-vector couplings and

$$\chi = (4 \sin^2\theta_W \cos^2\theta_W)^{-1} (s/m_{Z^0}^2 - s), \quad (3)$$

$$\sigma_{\text{point}} = 4\pi\alpha^2/3s, \quad (4)$$

and α and s have their usual meaning. In Eq. (3) we neglect the width of the Z^0 with respect to its mass. The vector and axial-vector couplings g_V and g_A are

given in the $SU(2)_L \otimes U(1)$ model by

$$g_V = -\frac{1}{2} + 2 \sin^2\theta_W, \quad g_A = -\frac{1}{2}. \quad (5)$$

Reaction (1) can be efficiently separated from the background reactions

$$\begin{aligned} e^+e^- &\rightarrow e^+e^-\mu^+\mu^-, \\ e^+e^- &\rightarrow \tau^+\tau^- \rightarrow \mu^+\mu^- + \text{neutrinos}, \end{aligned} \quad (6)$$

by selecting two muon events with an acollinearity angle smaller than 20° and for which at least one muon has a momentum greater than half of the beam energy. The remaining background from each reaction in (6) is less than 1%. We retain only events with $\cos\theta < 0.8$ since the acceptance in this angular region is flat and above 90%. (θ is the angle between the outgoing μ^- and the incoming e^- .) The measured data are corrected for acceptance and for QED radiative effects⁷ to order α^3 . The flat acceptance and the good resolution of the Mark J detector lead to a 4% systematic error in the cross section, of which 3% is from the uncertainty in the luminosity. With $\sin^2\theta_W = 0.22$, the standard model predicts that the weak vector couplings of the electron and muon are near zero, and thus at our energies $R_{\mu\mu}$ should deviate from the QED prediction by less than 1%. Our measurements at energies between 14 and 46.78 GeV agree well with this expectation, as shown in Table I.

The angular distribution of $e^+e^- \rightarrow \mu^+\mu^-$ has the form

$$d\sigma/d\cos\theta = (\pi\alpha^2/2s)[R_{\mu\mu}(1+\cos^2\theta) + B\cos\theta]. \quad (7)$$

The factor

$$B = -4\chi g_A^e g_A^\mu + 8\chi g_V^e g_V^\mu g_A^e g_A^\mu \quad (8)$$

$$A_{\mu\mu} = -\frac{3}{2}\chi \frac{g_A^e g_A^\mu (1 - 2\chi g_V^e g_V^\mu)}{(1 - 2\chi g_V^e g_V^\mu + \dots)} \approx -\frac{3}{2}\chi g_A^e g_A^\mu = -\frac{3}{8} \frac{1}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{m_{Z^0}^2 - s} g_A^e g_A^\mu. \quad (10)$$

The asymmetry is negative at energies below the Z^0 mass only if g_A^e and g_A^μ have the same sign.

QED alone produces a small positive forward-backward asymmetry, through the interference between the one- and two-photon exchange processes and between the initial- and final-state bremsstrahlung. The QED asymmetry is calculated by a Monte Carlo program of Behrends and Kleiss.⁷ It is found to be +1.4% for our detector and it is practically independent of energy. Theoretical calculations of the asymmetry, including the full electroweak radiative corrections, have been performed with different sets of renormalized physical parameters.⁸⁻¹¹ These calculations agree at the full one-loop level. The size of the electroweak radiative corrections varies with the choice of renormalized physical parameters. In the scheme¹⁰ employing the fine-structure constant, α , and the physical masses of the $W^\pm$ and the Z^0 , the size of the correction is +1.4% as previously obtained with pure QED. With use of this approach, the data then need be corrected only for QED radiative effects in order to be compared with the prediction of Eq. (10). Note that in this scheme the weak mixing angle θ_W is defined by

$$\cos\theta_W = m_W/m_{Z^0}, \quad (11)$$

TABLE I. Data sample, $R_{\mu\mu}$, $A_{\mu\mu}$, and the predicted values of the asymmetry, A_{th} .

$\sqrt{s}$ (GeV)	$\int L dt$ (pb ⁻¹)	$\mu\mu$ (No.)	$R_{\mu\mu}$ ^a	$A_{\mu\mu}$ (%)	A_{th} ^b (%)
14.0	1.5	472	1.04 ± 0.05	$+5.3 \pm 5.0$	-1.5
22.5	3.0	357	1.02 ± 0.05	-4.3 ± 6.1	-3.5
34.6	76.3	3658	0.98 ± 0.016	-11.7 ± 1.7	-8.5
39.8	9.3	341	1.01 ± 0.05	-10.9 ± 5.7	-12.0
44.6	23.5	673	0.99 ± 0.04	-16.7 ± 4.0	-16.0

^aThe error quoted is statistical. We estimate the systematic error to be ± 0.04 , mainly from the uncertainty in the luminosity.

^b $m_{Z^0} = 93$ GeV, $\sin^2\theta_W = 0.22$.

determines the forward-backward asymmetry which is given by

$$A_{\mu\mu} = \frac{N(\theta < 90^\circ) - N(\theta > 90^\circ)}{N(\theta < 90^\circ) + N(\theta > 90^\circ)} = \frac{3}{8} \frac{B}{R_{\mu\mu}}. \quad (9)$$

$N(\theta < 90^\circ)$ is the number of events with the μ^- in the forward hemisphere, and $N(\theta > 90^\circ)$ the number in the backward hemisphere. The asymmetry, $A_{\mu\mu}$, depends upon the axial-vector couplings of the electron and the muon and is practically independent of the vector couplings,

and is *not* modified by radiative corrections. If we fit Eq. (7) to the corrected data for $\cos\theta < 0.8$ and then extrapolate over the full angular range ($\cos\theta < 1$) we obtain the asymmetries at different energies as given in Table I and in Fig. 1. The errors shown are statistical. Systematic errors are less than 0.5%.^{2,3} The dashed curve in Fig. 1 is the standard-model prediction using $\sin^2\theta_W = 0.22$ and $m_{Z^0} = 93$ GeV. The agreement between our measured data and the predictions of the standard electroweak model is good.

Using Eqs. (2)–(10), we determine the values of $\sin^2\theta_W$ and m_{Z^0} , which are shown as 68% and 95% confidence level (C.L.) contours in Fig. 2. As discussed above, these contours include electroweak radiative corrections. In order to test the standard model, we compare these contours to the values of $\sin^2\theta_W$ and m_{Z^0} , determined by Arnison *et al.* (UA1)¹² and Bagnaia *et al.* (UA2)¹³ in experiments at CERN. Note that we use the measured masses, m_W and m_{Z^0} , from the UA1 and UA2 experiments, and Eq. (11) to determine their values of $\sin^2\theta_W$. This procedure is consistent with the definition in Eq. (11) and our electroweak radiative corrections.¹⁴ This comparison (Fig.

FIG. 1. $A_{\mu\mu}$ as a function of s . The dashed curve is the standard model prediction using $\sin^2\theta_W = 0.22$ and $m_{Z^0} = 93$ GeV.

2) is a direct test of the standard model with a purely leptonic reaction. We find agreement within the errors. Taking the average value of $m_{Z^0} = 93 \pm 2$ GeV from the CERN experiments,^{12,13} we find from our measurement

$$\sin^2\theta_W = 0.17 \pm_{0.02}^{+0.03} \pm 0.01,$$

and at the 95% C.L.

$$0.13 < \sin^2\theta_W < 0.25.$$

The first error is statistical, including the uncertainty in the Z^0 mass, the second is systematic. Combining all published PETRA and PEP results we obtain

$$\langle \sin^2\theta_W \rangle = 0.167 \pm_{0.015}^{+0.020}.$$

(See also Refs. 15 and 16.) Our result can be compared with that obtained from neutrino-electron and antineutrino-electron elastic scattering by Bergsma *et al.*¹⁷ and Ahrens *et al.*¹⁸ Their average value, uncorrected for radiative effects,¹⁹ is

$$\sin^2\theta_W = 0.212 \pm 0.023.$$

These are to be compared to the world average,²⁰

$$\langle \sin^2\theta_W \rangle = 0.217 \pm 0.014,$$

which is measured by lepton-nucleon and antilepton-nucleon inelastic scattering and includes radiative corrections.

Alternatively, we can determine m_{Z^0} from our data by using the world average for $\sin^2\theta_W$. We find

$$m_{Z^0} = 87 \pm_4^{\pm 5} \text{ GeV}.$$

The errors are 68% C.L. measurement errors. Use of all e^+e^- data changes the central value to 86 GeV and the error to $^{+3.3}_{-2.7}$. Taking $m_{Z^0} = 93$ GeV and

FIG. 2. Contours showing the correlation between $\sin^2\theta_W$ and m_{Z^0} . The points are measurements by Arnison *et al.* (UA1) and Bagnaia *et al.* (UA2); the error bars indicate the corresponding 68% C.L. contour value.

$\sin^2\theta_W = 0.217$, we find from our data that $g_A^e g_A^\mu = 0.30 \pm_{0.04}^{+0.03} \pm 0.02$.

Our measurement of $R_{\mu\mu}$ and $A_{\mu\mu}$ also allows us to test models with extended gauge groups. In Ref. 3 we have described a test at $\langle \sqrt{s} \rangle = 35$ GeV for $SU(2) \otimes U(1) \otimes G$ models. These models are described by the Hamiltonian for neutral currents

$$H_{NC} = (4G_F/\sqrt{2})[(j_\mu^{(3)} - \sin^2\theta_W j_\mu^{em})^2 + C(j_\mu^{em})^2]. \quad (12)$$

C is a constant which depends upon the group G , $j_\mu^{(3)}$ is the third component of the weak isospin current, and G_F is the Fermi weak-coupling constant. Our new data at higher average energy, $\langle \sqrt{s} \rangle = 44$ GeV, determine the parameter $C < 0.035$, at 95% C.L. We have also tested the left-right symmetric model with a $SU(2)_L \otimes SU(2)_R \otimes U(1)$ gauge group.²¹ This model has two neutral gauge bosons and it is described by a Lagrangian of the type

$$L = gJ_L W_L + gJ_R W_R + g_Y J^Y B^Y. \quad (13)$$

g_Y is the hypercharge coupling constant. The symmetry breaking is arranged in the Higgs sector such that $m_{W_L} \ll m_{W_R}$ and only left-handed currents contribute at low energies. Using the formalism given in Ref. 21, we find for the masses of the neutral bosons

$$m_{Z_2} > 150 \text{ GeV with 95\% C.L.,}$$

with

$$m_{Z_1} = 85\text{--}100 \text{ GeV}.$$

In summary: (1) Our measurements of the muon charge asymmetry and the total cross section in the reaction $e^+e^- \rightarrow \mu^+\mu^-$ support the standard elec-

troweak theory. (2) We obtain $\sin^2\theta_W = 0.17^{+0.03}_{-0.02} \pm 0.01$ for $m_{Z^0} = 93 \pm 2$ GeV and $m_{Z^0} = 87^{+5}_{-4}$ GeV for $\sin^2\theta_W = 0.217 \pm 0.014$ from a purely leptonic reaction. (3) In a left-right symmetric model with the $SU(2)_L \otimes SU(2)_R \otimes U(1)$ extended gauge group, we find the mass of $m_{Z_2} > 150$ GeV with 95% C.L. with $m_{Z_1} = 85\text{--}100$ GeV.

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