Weak Neutral Current Effects in $e^+e^- \to \mu^+\mu^-$ at 29 GeV[*]

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ABSTRACT

We present a measurement of the cross section for production of collinear muon pairs based upon a sample of more than 10000 events observed in the MAC detector at PEP. From the angular asymmetry $A_{\mu\mu} = -0.058 \pm 0.010$ we find the axial vector weak neutral coupling to be given by $g_A{}^e g_A{}^\mu = 0.24 \pm 0.04$.

The production of muon pairs in the reaction

$$e^+ e^- \rightarrow \mu^+ \mu^- \tag{1}$$

is sensitive to the effects of the axial-vector part of the weak neutral current through an antisymmetric contribution to the angular distribution. We report a measurement of the muon pair production cross section obtained with the MAC detector operating at the SLAC storage ring, PEP. The present data sample includes the one used for our previously published measurement[1] and is about three times as large.

The MAC detector, described in detail in ref. 2, includes a calorimeter/muon identifier of >95% solid angular acceptance. The calorimeter is composed of 91 cm of steel absorber surrounding the interaction point as a hexagonal prism with endcaps, with proportional wire chambers interspersed at 2.5-cm intervals to detect ionization from traversing particles. The steel is magnetized by toroid coils with a strength of about 18 kGauss, and is surrounded by 4-6 layers of drift chambers for tracking muons. Inside the iron calorimeter is a lead plate shower

chamber to detect photon and electron showers in the central region, $|\cos\theta| \leq .8$; the inner portions of the endcap iron calorimeters serve the same function in the polar regions. Scintillators placed three plates behind the entrance faces of the iron calorimeter provide triggering and timing. Innermost is a ten-layer drift chamber in a 5.7 kGauss solenoidal magnetic field.

The data reported here resulted from an exposure of 143 inverse picobarns at the center-of-mass energy 29 GeV. The pertinent trigger for this measurement was formed by the coincidence between pairs of scintillators in opposing sextants or endcap quadrants, or by at least one penetrating track as defined by a hit cluster in the central drift chamber in coincidence with a 400-MeV or greater pulse in the azimuthally matched calorimeter and scintillator sextant. Of the events read into the online computer, those which had clusters of central drift chamber hits in the appropriate azimuthal regions were recorded for further analysis. This requirement avoided logging of cosmic rays which missed the central drift chamber.

After reconstruction, events were taken which had two central drift chamber tracks that formed a vertex compatible with the known beam intersection volume, i.e., a satisfactory x^2 for the vertex-constrained fit. Each track was extrapolated into the calorimeters to be associated with the energy-deposition data. A particle was classified as a muon if it appeared to be minimum-ionizing through the calorimeters, or if an associated track segment appeared in the outer drift chambers. It was required that both tracks be classified as muons for an event to be considered further.

Events passing these criteria included a large background of cosmic rays and of muon pairs from the two-photon reaction,

$$ee \rightarrow (ee)\mu\mu \tag{2}$$

with undetected electrons. Both backgrounds were reduced by a large factor by requiring a satisfactory x^2 value for both muon tracks to be assigned energy equal to the beam energy, based upon both central drift chamber and toroid spectrometer measurements. Cosmic rays were removed by cuts on the track-associated scintillator timing and by loose cuts on the vertex position. The distributions in time-of-flight and in the longitudinal beam position of events which passed the timing requirements indicates that fewer than 0.2% of the remaining sample are cosmic rays. Two-photon induced pairs were removed by requiring the muons to be collinear (i.e., oppositely-directed) within 10°. According to a Monte Carlo calculation[3], the surviving background from (2) amounts to 0.3% of the signal.

Events coming from Bhabha scattering,

$$e^+e^- \rightarrow e^+e^-, \tag{3}$$

if misidentified and included in the sample, would represent a serious background because of the large asymmetry of reaction (3). Particular attention was paid to elimination of these events in the choice of criteria for classifying muons. From a small subsample of events that fail slightly more restrictive criteria we estimate the fraction of Bhabha events in the sample to be less than 0.3%.

The remaining background was from the reaction

$$e^+e^- \rightarrow \tau^+\tau^-,$$ (4)

followed by decay of the τs to muons or penetrating charged pions, perhaps accompanied by π^0s. The fraction of these events in the sample was calculated by Monte Carlo[4] to be 0.8% compared with the signal.

The final sample contains 10258 events, of which about 80 are from background processes discussed above, mainly reaction (4). None of the background reactions, except (3), affects the angular distribution strongly; in particular, their charge asymmetries are mild. Asymmetric biases in the detection efficiency are minuscule, since forward and backward events are distinguished by the sign of the very small curvature of the tracks in the solenoid and toroid spectrometers. A bias would be produced by an end-to-end azimuthal twist of the central drift chamber. Such an effect has been detected (and corrected) with the Bhabha event sample, which is far more sensitive because of the typically steep dip angle and extreme asymmetry of these events. Even before correction of the twist, the false asymmetry for muon pairs was negligible. Both the solenoid and toroid field polarities were reversed periodically during the data collection. A negligible dilution of the asymmetry was caused by misassignment of the sign of charge of the muons, which occurred in fewer than 0.3% of the events.

The detection efficiency of the central drift chamber as a function of production angle was determined from a Monte Carlo calculation. The redundant calorimeter/outer drift chamber particle identification permitted determination of the identification efficiency directly from the data. The efficiency of the scintillator system was obtained from a

sample of events in which only one in-time scintillator was required. The overall geometrical plus detector efficiency was such that about 71% of all collinear pairs produced (in 4π steradians) were accepted into the sample.

The production of muon pairs is described according to the standard electroweak theory[5] by

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[(1+a_1)(1+\cos^2\theta) + 2a_2\cos\theta\right],$$

where to order αG we have

$$a_{1,2} = g^e{}_{V,A}\, g^\mu{}_{V,A}\, \frac{1}{\pi\alpha}\, \frac{G}{\sqrt{2}}\, \frac{-s}{1-s/M_Z^2}.$$

(5)

Here θ is the angle between the μ^+ and the incident e^+. Equation (5) includes the contributions of the single photon annihilation diagram and of its interference with annihilation through the neutral weak intermediate vector boson, Z^0, of mass M_Z.

Radiative corrections to equation (5) have been calculated with the Monte Carlo program of Berends and Kleiss[6], which includes terms of order α^3. These terms contribute a charge asymmetry of +0.028. Checks on the ability of the calculation to model the data are provided by the measured distribution in the noncollinearity angle[1], and by data on radiative muon pair production from this experiment[7].

The differential cross section after radiative corrections is shown in Fig. 1, with the overall normalization of the data adjusted (see below) to agree with that of the theoretical cross section. A maximum-

likelihood calculation determined the best-fit value of a_2, from which we find the charge asymmetry,

$$A_{\mu\mu} \equiv \frac{N_+ - N_-}{N_+ + N_-} = -\frac{3}{4}\frac{a_2}{1+a_1}, \tag{6}$$

where N_+ (N_-) is the number of events having the μ^+ produced at positive (negative) $\cos\theta$, extrapolated to 4π angular acceptance. With the assumption that $a_1 \ll 1$ (see below), the result is

$$A_{\mu\mu} = -0.058 \pm 0.010 \pm 0.003.$$

The second error quoted is systematic and is attributable mainly to possible Bhabha background. With the standard-model value $g_A^e g_A^\mu = 0.25$ and $M_Z = 90$ GeV, equation (5) predicts $A_{\mu\mu} = -0.063$ at $s = (29 \text{ GeV})^2$. A recent calculation[8] including radiative corrections to Z^0-exchange diagrams leads to the slightly lower prediction $A_{\mu\mu} = -0.060$. Taking this effect into account the product of electron and muon axial-vector coupling constants from the fit is

$$g_A^e g_A^\mu = 0.24 \pm 0.04,$$

in good agreement with the theory and with other published measurements[9].

From equation (5) we see that the muon pair cross section depends upon the vector coupling constants via a normalization shift. The standard-model prediction is

$$g_V^e g_V^\mu = -\frac{1}{4}(1-4\sin^2\theta_W)^2, \tag{7}$$

where θ_W is the Weinberg angle. Previous experiments[10] give

$$\sin^2\theta_W = 0.23 \pm 0.01,$$

hence $g_V{}^e g_V{}^\mu = 3.6 \times 10^{-3}$. The resulting contribution to a_1 is smaller than those of higher order terms, implying $a_1 \ll 0.01$. The absolute cross section from a subset of our data is $0.976 \pm 0.014 \pm 0.034$ times the pure QED prediction (eqn. 5 with $a_1 = a_2 = 0$). From this scale factor we find

$$g_V{}^e g_V{}^\mu = 0.07 \pm 0.11.$$

The precision of the measurement of the vector couplings is limited by systematic uncertainties in the normalization.

In conclusion, we have made a precision measurement of the effect of the weak neutral current in muon pair production by electron-positron annihilation.

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Figure Caption

Fig. 1. Differential cross section for muon pair production, after

radiative correction. The curve is the result of the fit described
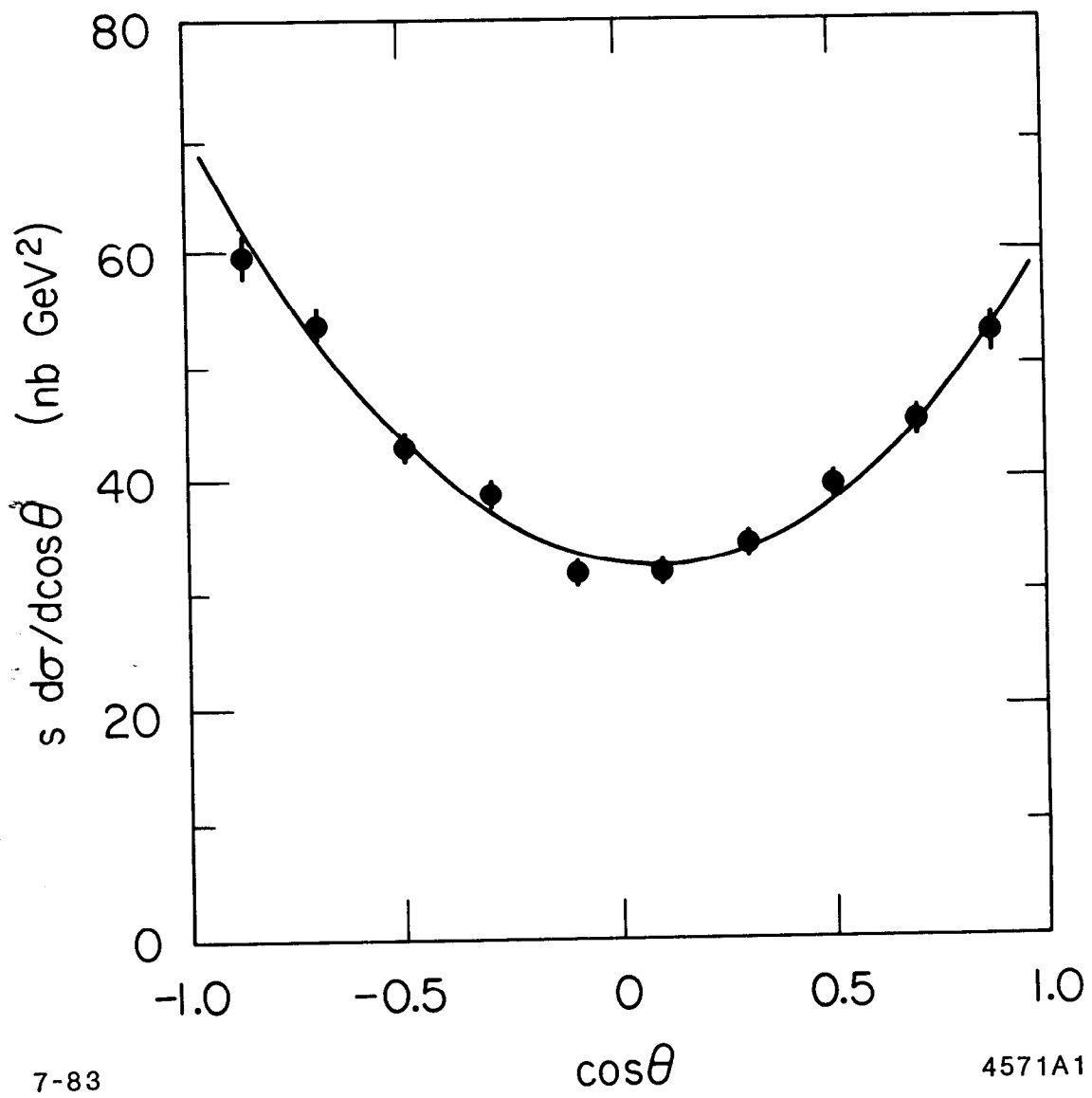
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80

60

s dσ/dcosθ (nb GeV²)

40

20

0

-1.0   -0.5   0   0.5   1.0

cosθ

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Fig. 1