Limits on Strength of Neutral Currents from $e^+e^- \rightarrow \mu^+\mu^-$

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The reaction $e^+e^- \rightarrow \mu^+\mu^-$ has been measured in the center-of-mass energy range 5.8–7.4 GeV. The polar-angle asymmetry agrees with second-order quantum electrodynamics. From this a 95% confidence limit of $M_Z > 53g_a/e$ GeV is placed on the mass to coupling constant ratio for a neutral vector boson.

We report on a measurement of the polar-angle asymmetry of muon-pair production in electron-positron annihilation. The main contribution to the cross section for this reaction is the quantum electrodynamic process of one-photon annihilation. Higher-order quantum electrodynamic (QED) processes can interfere with the one-photon term and produce an angular asymmetry in muon-pair production, but this asymmetry is well understood and calculable.[1] Other processes, such as the axial-vector part of the weak interaction, can also produce an asymmetry[2] and it is these other processes that we investigate here. In particular, gauge theoretical models of the neutral-current weak interactions predict an asymmetry which depends on the ratio of coupling to mass of the neutral gauge boson, and our data set a limit on this quantity.

The data were taken with the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory magnetic detector at the SPEAR electron-positron storage ring of the Stanford Linear Accelerator Center. The apparatus has been described previously.[3] Candidate muon-pair events were selected by requiring that each event have only two tracks originating from a volume of 4 cm radius by 80 cm length centered on the e^+e^- collision point and coaxial with the storage-ring beams. The two tracks were required to be oppositely charged, to have flight times to a set of cylindrical scintillation counters located at a radius of 1.5 m from the electron-positron beam axis that are equal to within 3 nsec, to be collinear to $\leq 10°$, and to each have momenta greater than half of the storage-ring beam energy. With these topological, kinematic, and time-of-flight cuts the only significant background was Bhabha scattering.

Bhabha scattering was separated from muon-pair production by pulse height in a cylindrical set of 24 lead-scintillator-sandwich shower counters outside the time-of-flight counter system. The scatter plot of Fig. 1 shows the relative energy deposited by one track in these shower counters versus the energy deposited by the other track. The dashed line indicates the cuts used to separate e^+e^- pairs from muon pairs. Note that Bhabhas near the edge of a shower counter may have a small pulse height due to the shower going out the edge of the counter. To prevent these from leaking into the muon sample, events where both particles are within 2.3 cm of a shower counter edge were thrown out. There is clearly no significant Bhabha background in the final data sample.

The final data sample consists of approximately 11 000 muon pairs, taken at center-of-mass energies from 5.8 to 7.4 GeV with a root-mean-square center-of-mass energy of 6.8 GeV. The polar-angle distribution of these events is shown in Fig. 2.[4] The solid line is the angular distribution predicted by second-order QED.

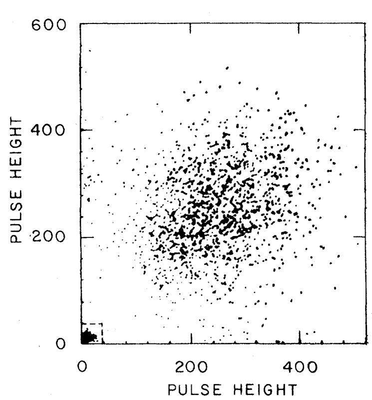

FIG. 1. Scatter plot of pulse height of the positive particle vs pulse height of the negative particle. The events plotted have passed all of the cuts except for the pulse-height cut. Only 1% of the data is shown here. The dashed line shows the pulse-height cut.

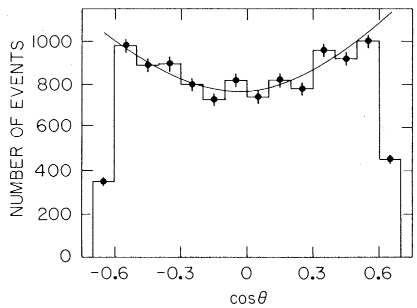

FIG. 2. Angular distribution for $e^+e^- \to \mu^+\mu^-$. θ is the angle between the incoming e^+ direction and the outgoing μ^+ direction. The sharp dropoff for $|\cos\theta| > 0.6$ is due to the angular acceptance of the detector. The line is the QED prediction, normalized to the data.

A simple way to compare these data to theory is to form the asymmetry

$$A_D = \frac{\int_0^z [\sigma(\theta) - \sigma(\pi - \theta)] d\cos\theta}{\int_0^z [\sigma(\theta) + \sigma(\pi - \theta)] d\cos\theta}, \qquad (1)$$

where $\sigma(\theta)$ is the cross section for producing a μ^+ at the polar angle θ, and the upper limit of integration corresponds to the boundary of the acceptance region of the detector. Using the asymmetry has several advantages. First, absolute normalization is not required. Second, effects due to the angular acceptance and the efficiency of the detector cancel out. This cancellation occurs because both $\sigma(\theta)$ and $\sigma(\pi - \theta)$ depend on the efficiency at angle θ. That is, to measure $\sigma(\theta)$ the μ^+ must be detected at θ while to measure $\sigma(\pi - \theta)$ the μ^- must be detected at θ. Since the detector is azimuthally symmetric and the magnetic field bends the particles in the azimuthal direction, the efficiencies for detecting μ^+ and μ^- at angle θ are the same. So to first order an inefficiency cancels out in the subtraction to form A_D. For example, if the efficiency were only 90% for $0.5 < \cos\theta < 0.6$ and 100% elsewhere, A_D changes by only 1% of the value it would have for a completely efficient detector. Thus, to calculate A_D, no corrections are required and the data for Fig. 2 give

$$A_D = 0.013 \pm 0.010 \qquad (2)$$

in the region $|\cos\theta| < 0.6$.

Two sources of this asymmetry are considered: QED radiative corrections and neutral-current weak interactions. Since both of these cause an asymmetry by interference of a small term with the large annihilation term, their asymmetries will add (interference of the small terms with each other is insignificant). The radiative corrections for this reaction have been calculated from the work of Berends, Gaemers, and Gastmans.[1] For $|\cos\theta| < 0.6$ this gives an asymmetry of 0.0155 ± 0.0008. Subtracting this from the asymmetry in the data we obtain a non-QED asymmetry

$$A_W = -0.003 \pm 0.010, \qquad (3)$$

and (at 90% central confidence level)

$$-0.019 < A_W < 0.013. \qquad (4)$$

To see what constraints this places on theories of the weak interaction, it is convenient to extrapolate our data to all angles. To do this a theoretical form for the angular distribution is needed. A fairly general theory which assumes only μ-e universality and the existence of a neutral boson Z^0 with mass, width, and coupling constants of M, Γ, g_v, and g_a gives[5]

$$\begin{aligned} \frac{4s}{\alpha^2}\frac{d\sigma^{\mu\mu}}{d\Omega} &= F_1(s)(1+\cos^2\theta) + 2F_3(s)\cos\theta, \\ F_1 &= 1 + 2g_v^2\mathrm{Re}(R) + (g_v^4 + 2g_v^2g_a^2 + g_a^4)|R|^2, \\ F_3 &= 2g_a^2\,\mathrm{Re}(R) + (4g_v^2g_a^2)|R|^2, \\ R &= \frac{s}{e^2(s - M_Z^2 + iM_Z\Gamma)}. \end{aligned} \qquad (5)$$

This gives an asymmetry integrated over all angles of

$$A_{\mathrm{weak}}^{\mu\mu} = \tfrac{3}{4}F_3/F_1. \qquad (6)$$

Using this angular dependence for the cross section it is simple to extrapolate the data with $|\cos\theta| < 0.6$ to all angles. This gives

$$-0.025 < A_{\mathrm{weak}}^{\mu\mu} < 0.017 \qquad (7)$$

(at 90% central confidence level).

Assuming that $M_Z \geq 30$ GeV and $\Gamma \ll M_Z$, i.e., that we are well below resonance, the expressions for F_1 and F_3 simplify to give

$$A_{\mathrm{weak}}^{\mu\mu} = -\tfrac{3}{2}g_a^2 s/e^2M_Z^2$$

so that the restriction placed on this theory is[6]

$$M_Z > 53g_a/e \text{ GeV} \qquad (8)$$

(95% confidence).

We now compare our results with some more specific models. The Weinberg model[2] predicts $M_Z = 150g_a/e$ GeV, for all $\sin\theta_W$, and is consistent with this experiment. On the other hand, the model of Shafi and Wetterich[7] which has three neutral gauge bosons, one of which is very light, predicts a much larger asymmetry. Our data are inconsistent with the predictions given in Ref. 7. The model of Elias, Pati, and Salam[8] uses the $SU(4)^4$ symmetry. With the parameters given in their paper, our data restrict the mass of the neutral boson to be greater than 55 GeV.

Previously a limit on M_Z was set by looking at the energy dependence of the neutrino neutral-current cross section. Using data from a single experiment, this gives $M_Z > 3$ GeV.[9] Comparison between the two experiments is made difficult by problems of relative normalization. The limit placed in this way is $M_Z > 10$ GeV.[10]

In conclusion, we see no asymmetry in the reaction $e^+e^- \to \mu^+\mu^-$ other than that caused by second-order QED, thus setting a lower limit on the ratio of mass to coupling constant for a neutral vector boson.

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[6]Since the theory predicts a specific sign for the asymmetry, we are only concerned with one tail of the distribution; so the 90% confidence level becomes 95%.

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Linearizing the Volkov-Akulov Model

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The nonlinear realization of supersymmetry of Volkov and Akulov is related to a constrained linear realization in two and four dimensions.

One of the earliest realizations of supersymmetry was the nonlinear model of Volkov and Akulov[1]; this was soon followed by the linear scalar multiplet of Wess and Zumino.[2] It has been asserted[3] that the two models are related in the same sense that the nonlinear σ model is related to linear realizations of $O(n)$ symmetry. In this Letter I show that this is indeed the case; specifically, I show that if one applies the correct supersymmetrically invariant constraints to the linear multiplet, one is left with the Volkov-Akulov model.

I first consider the two-dimensional case[4]: The linear scalar multiplet consists of two scalar fields A and F and a Majorana spinor ψ with transformations

$$\delta A = \bar{\epsilon}\psi, \quad \delta\psi = (F - i\partial\!\!\!/ A)\epsilon, \quad \delta F = -\bar{\epsilon}i\partial\!\!\!/\psi. \tag{1}$$

A supersymmetric action for these fields is

$$S_L = \tfrac{1}{2}\int d^2x[(\partial A)^2 + \bar{\psi}i\partial\!\!\!/\psi + F^2]. \tag{2}$$

This can be rewritten in superspace notation by introducing a superfield Φ,

$$\Phi = A + \bar{\theta}\psi + \tfrac{1}{2}\bar{\theta}\theta F. \tag{3}$$

Then

$$S_L = \tfrac{1}{4}\int d^2x d\bar{\theta}\, d\theta\, (\Phi\bar{P}P\Phi), \tag{4}$$

where $P = \partial/\partial\bar{\theta} - i\partial\!\!\!/\theta$. The supersymmetry transformations (1) are generated by $Q = \partial/\partial\bar{\theta} + i\partial\!\!\!/\theta$, $\delta\Phi = [\bar{\epsilon}Q, \Phi]$.

The Volkov-Akulov model in two dimensions consists of a single Majorana spinor λ with transformation

$$\delta\lambda = \epsilon - (\bar{\epsilon}i\gamma_\mu\lambda)\partial_\mu\lambda \tag{5}$$

and invariant action

$$\begin{aligned} S_{VA} &= +\tfrac{1}{2}\int d^2x \det(\eta_{a\mu} - \bar{\lambda}i\gamma_a\partial_\mu\lambda) \\ &\equiv \tfrac{1}{2}\int d^2x \det(V_{a\mu}) \\ &= -\tfrac{1}{2}\int d^2x[1 - \bar{\lambda}i\partial\!\!\!/\lambda - \tfrac{1}{2}\bar{\lambda}\lambda\epsilon_{\mu\nu}(a_\mu\bar{\lambda}\gamma_5\partial_\nu\lambda)]. \end{aligned} \tag{6}$$

