Study of acollinear muon pair production in e^+e^- interactions at $E_{\text{c.m.}}=29$ GeV

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(Received 28 June 1983)

We have studied the production of acollinear muon pairs in e^+e^- interactions using the MAC detector at PEP. The results are totally accounted for by the QED processes $e^+e^-\to e^+e^-\mu^+\mu^-$ and $e^+e^-\to\mu^+\mu^-\gamma$ in which only the muon pairs are detected. We have also searched for the production of the supersymmetric partners of the muon. The existence of a spin-0 supersymmetric partner of the muon with a mass <13.8 GeV/c^2 is excluded at the 95% confidence level.

The observation of dimuon final states with missing momentum in e^+e^- colliding-beam interactions can be an indication of the production of new particles which decay to muons and noninteracting neutral particles. For example, the pair production of the spin-0 partners of the muon [see Fig. 1(a)], s_μ and t_μ, predicted by supersymmetric theories,[1] would result in a final state having two muons and two photinos. The photinos are presumed to interact only weakly with matter and therefore are not likely to be detected. At PEP energies, the QED reaction

$$e^+e^-\to e^+e^-\mu^+\mu^- , \tag{1}$$

in which the muon pairs are produced by the collision of the bremsstrahlung photons from the beam electrons [see Fig. 1(b)], occurs at a rate about three orders of magnitude higher than the annihilation cross section.[2] [The total cross section for reaction (1) is about 120 nb at a center-of-mass energy $E_{\text{c.m.}}=29$ GeV.] Reaction (1) usually occurs with the two beam electrons scattered by small angles and therefore not detected, resulting in a final state with only two muons visible. This overwhelming QED background makes the detection of new particle produc-

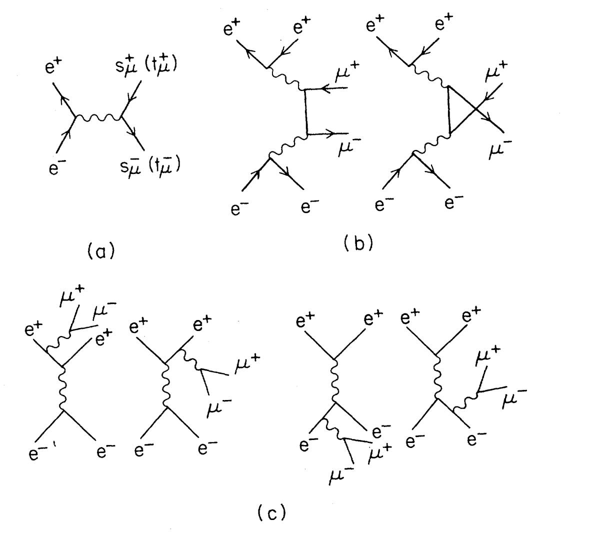

FIG. 1. Feynman diagrams for the processes (a) $e^+e^-\to s_\mu^+s_\mu^-$, (b) $e^+e^-\to e^+e^-\mu^+\mu^-$, and (c) $e^+e^-\to e^+e^-\mu^+\mu^-$.

tion with a similar final state difficult. However, in contrast to muon pairs from the two-photon reaction (1) which are predominantly coplanar with the beam, the muons from the decay of s_μ pairs (we assume s_μ to be the lighter of the supersymmetric partners of the muon) are in general acoplanar. In this paper, we present an analysis of the dimuon events which have no photon in the detector and the two muons are acollinear by more than 10°. (The studies of collinear and radiative muon pair production via one-photon annihilation have been published previously.[3]) We have specifically searched for acoplanar muon pairs as evidence for pair production of s_μ's. The data were taken by using the MAC detector at the PEP e^+e^- storage ring at the Stanford Linear Accelerator Center (SLAC). The total integrated luminosity is 46.3 pb^{-1}, all taken at a center-of-mass energy of 29 GeV.

The MAC detector and its trigger have been described elsewhere.[4] Described briefly, the MAC detector consists of a cylindrical inner detector with 10 layers of drift cells, surrounded in succession by a solenoidal magnet coil, an electromagnetic calorimeter, a set of 144 scintillation trigger counters, hadron calorimeters, and muon drift tubes. Charged particles are first momentum-analyzed in a magnetic field of about 5.7 kG along the beam direction with a resolution of $\delta p/p = 0.065p$ (p in GeV/c). The energy of electrons and photons is measured by a Pb—proportional-wire-chamber (PWC) sandwich electromagnetic calorimeter in the central section and by Fe-PWC sandwich end-cap electromagnetic calorimeters. The hadron calorimeters are steel plates sampled by PWC's with a total of about 5 absorption lengths. The steel plates are toroidally magnetized to about 17 kG and are surrounded by drift tubes to serve as a muon spectrometer. The MAC detector covers the entire solid angle with $|\cos\theta| < 0.98$ with electromagnetic and hadronic calorimetry. The relevant trigger for the present study is the "single-muon processor" which requires a coincidence of (1) clusters of hits in the central drift chambers, (2) at least one scintillator-trigger-counter hit, and (3) more than 400 MeV of energy deposited in the hadron calorimeter, all in the same 60° azimuthal sector. Most of the data were taken with an additional trigger which accepts one or two single-muon triggers. This redundancy allows us to determine the efficiency of the single-muon trigger to be 95% for muons with a momentum > 1.5 GeV/c.

The dimuon events were selected off-line by requiring (1) two oppositely charged tracks both with momenta greater than 1.5 GeV/c, (2) the polar angle of each track to be more than 20° from the beam, (3) the acollinearity angle between the two tracks (ξ) to be greater than 10°, (4) no shower of more than 1.0 GeV in the shower chambers, (5) the timing of both of the struck scintillation counters to be within 6 ns from the expected time of flight from the interaction point, (6) the vertex position of the two tracks along the beam to be within 5.5 cm of the interaction point, (7) the total energy deposited in the central and the end-cap hadron calorimeters within a cone of 10° around the extrapolated trajectory of the inner-drift-chamber tracks to be greater than the electromagnetic energy deposited in the same cone, and (8) the ratio of the energy deposited in the shower chambers within the same 10° cone to the momentum of the track to be less than 0.7.

Cut 3 is designed to remove cosmic rays and muon pairs from the one-photon muon pair production process $e^+e^- \to \mu^+\mu^-$, which are mostly collinear. Radiative events $e^+e^- \to \mu^+\mu^-\gamma$ with the photon detected by the detector are removed by cut 4. The large acceptance of the MAC detector for muons and photons constrains the unseen particles to polar angles less than about 12° from the beam, offering a large rejection factor against these background events. Remaining cosmic-ray background is removed by the timing (5) and vertex (6) constraints. Background events with at least one electron or pion in the final state, such as $e^+e^- \to \tau^+\tau^- \to \mu^\pm(e/\pi)^\mp$, $e^+e^- \to e^+e^-e^+e^-$, and $e^+e^- \to e^+e^-\pi^+\pi^-$, are removed by cuts 7 and 8. In an integrated luminosity of 46.3 pb^{-1}, we are left with 5458 events. The luminosity was determined by (1) a small-angle luminosity monitor, (2) measuring large-angle Bhabha scattering, and (3) measuring the reaction $e^+e^- \to \mu^+\mu^-$[3]. We have used the weighted average of the three measurements to normalize our data. The systematic error of the luminosity was estimated to be about 2%.

We have considered the following sources of background:

(1) The remaining beam-gas and cosmic-ray background was estimated to be less than 0.5% by a study of the vertex distribution of the events which passed all the cuts except 6.

(2) The remaining contamination from one-photon muon pair production was calculated by a Monte Carlo program of Berends and Kleiss[5] to be 12.1% and was subtracted from the data.

(3) The background from τ pair production was calculated by a similar Monte Carlo program to be 1.3% and was subtracted from the data.

(4) The background due to the processes $e^+e^- \to e^+e^-\tau^+\tau^-$, $e^+e^- \to e^+e^-e^+e^-$, and $e^+e^- \to e^+e^-\pi^+\pi^-$ was determined by Monte Carlo studies to be negligible.

We have compared our results with a Monte Carlo simulation using Vermaseren's program[6] for reaction (1), taking into account the Feynman diagrams shown in Fig. 1(b). According to this calculation, most of the final-state electrons are scattered < 10° from the beam and are therefore not detected by the MAC detector. The number of $e\mu\mu$ events observed is also in good agreement with the Monte Carlo predictions. A more detailed analysis of these single-tag events will be given elsewhere. We have studied the contribution arising from the initial- and final-state bremsstrahlung photons converting to muon pairs [see Fig. 1(c)] and this source was found to be negligible. Higher-order QED radiative corrections are not included in the program. Recent calculations indicate that such corrections are 1 to 2 percent.[7] After correcting for the trigger inefficiency (2.5%) which was not simulated by the Monte Carlo, the number of background-subtracted events is 4849±74(statistical)±97(systematic), where the systematic error mainly comes from the uncertainty in the background subtraction. This agrees very well with the predicted number of 5090±260(systematic) events from Monte Carlo calculations. The major error in the Monte

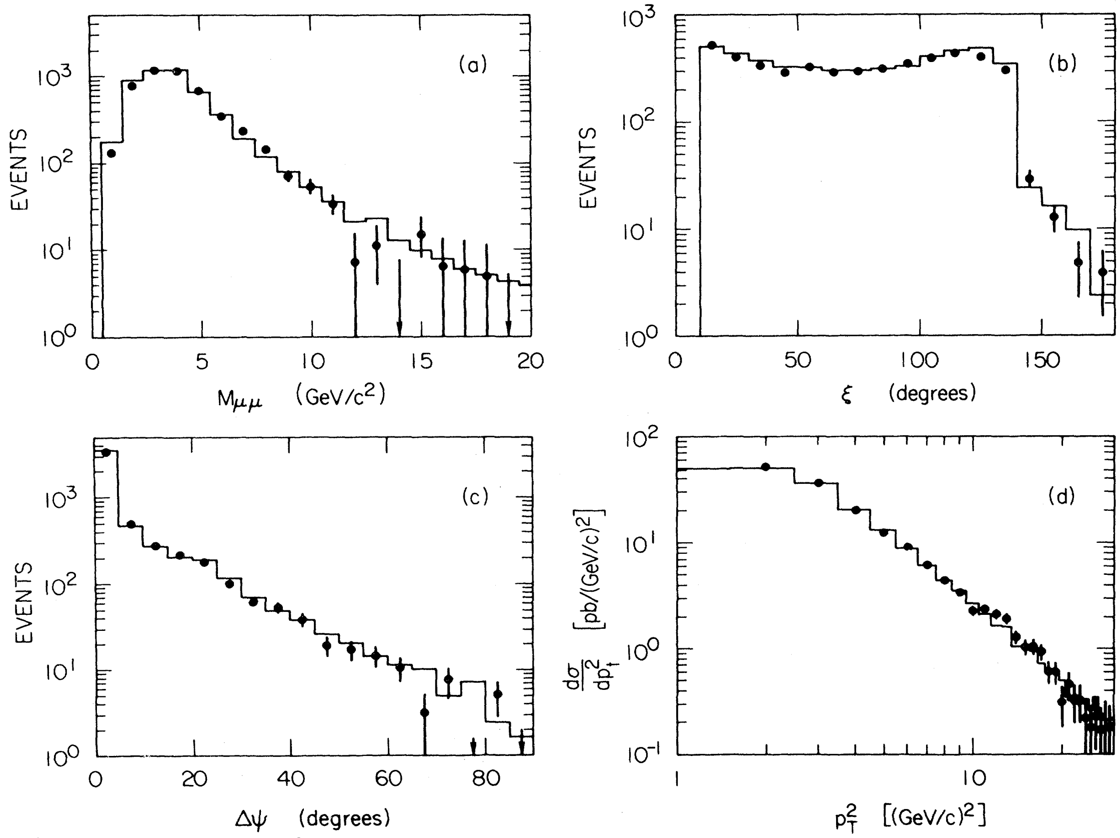

FIG. 2. The observed distribution of (a) the invariant mass, (b) the acollinearity angle, (c) the acoplanarity angle, and (d) the p_t^2 of the muon pairs compared with Monte Carlo predictions (histogram).

Carlo prediction comes from uncertainties in the total integrated luminosity and acceptance.

We have also compared the various observed kinematic quantities with Monte Carlo predictions. Backgrounds were subtracted from the observed distributions bin by bin. Figure 2(a) is the invariant-mass distribution of the two muons ($m_{\mu\mu}$) and is clearly in good agreement with the Monte Carlo predictions. The absence of structure in the invariant-mass distribution excludes the production of a new resonant state which decays only to two muons. The acollinearity angle distribution is shown in Fig. 2(b) and is also in good agreement with the Monte Carlo predictions. The acoplanarity angle distribution is shown in Fig. 2(c). The acoplanarity angle is defined in the present analysis as[8]

$$\Delta\psi = |\, 90^\circ - \arccos(\hat{n}\cdot\hat{z})\,| ,$$

where $\hat{n}$ is a unit vector perpendicular to the plane containing the two muons and $\hat{z}$ is a unit vector along the beam direction. The distribution peaks at small acoplanarity angles, consistent with the fact that the missing momentum is along the beam direction. The distribution also agrees in detail with the Monte Carlo predictions.

Figure 2(d) shows the differential cross section as a function of the square of the transverse momentum of the muons relative to the beam direction (p_t^2). This distribution has been corrected for trigger inefficiency. The observed distribution agrees very well with the Monte Carlo predictions and has a χ^2 of 1.04 per degree of freedom. In the limit of infinite center of mass energy, the cross section is expected to follow[2]

$$\frac{d\sigma}{dp_t^2} = A p_t^{-4} .$$

We have fitted the distribution to a power-law depen-

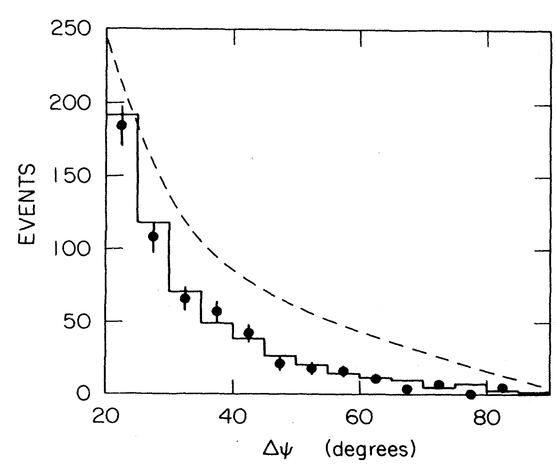

FIG. 3. The observed acoplanarity distribution of the muon pairs compared with the QED Monte Carlo predictions (histogram). The dashed curve includes 7-GeV/c^2 s_μ pairs.

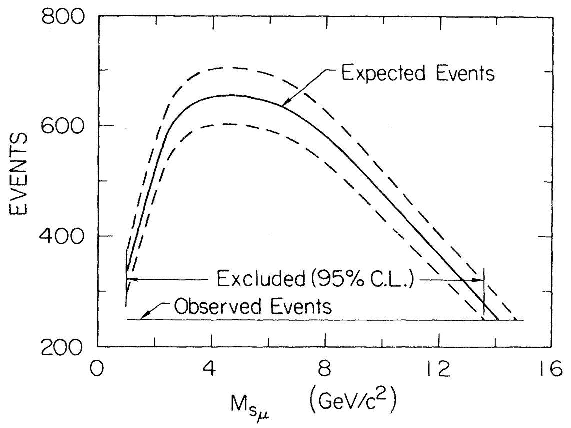

FIG. 4. Monte Carlo expectations including s_μ pair production as a function of the mass of s_μ. The horizontal line is the number of observed events.

dence, namely, $d\sigma/dp_t^2 = Ap_t^{-n}$ for p_t^2 in the range of 3—30 GeV^2/c^2. We obtained a value of 4.52 ± 0.08 for n and 463 ± 35 pb/(GeV^2/c^2) for A with a χ^2 of 1.41 per degree of freedom. The experimental value of A is in good agreement with results of analytical calculations,[9] but the value of n disagrees with the asymptotic value of 4. A similar fit to the Monte Carlo events yields $n = 4.56\pm0.12$ with a χ^2 of 4.11 per degree of freedom. The large χ^2 indicates that the distribution may deviate from a simple power law with a constant n. We have tried the hypothesis that n is a function of p_t^2 with the following dependence:

$$n = a + bp_t^2 .$$

Fits to both the data and Monte Carlo events with this hypothesis have improved χ^2. The values of a and b for the data are 4.00 ± 0.12 and $0.019\pm0.004/(\mathrm{GeV}^2/c^2)$, respectively, with a χ^2 of 28.5 for 25 degrees of freedom. The corresponding values for Monte Carlo events are 4.09 ± 0.08 and $0.015\pm0.003/(\mathrm{GeV}^2/c^2)$. It is interesting to note that the asymptotic value of n (as p_t^2 approaches 0) is indeed very close to 4. A stronger test of this hypothesis will require substantially more data. The Mark-J collaboration has studied the same process and obtained a value of $n = 4.9\pm0.2$ in a similar p_t^2 range.[10]

It is apparent from Fig. 2(c) that the QED cross section for dimuon events with large $\Delta\psi$ from photon-photon collisions is small. This essentially QED background-free region is a good hunting ground for anomalous muon pair production. To search for a signal coming from the pair production of s_μ's, we further select events with $\Delta\psi > 30°$, and compare the number of observed events (249) with the expectations from Monte Carlo calculations. The s_μ pair production cross section is given by[1]

$$\frac{d\sigma(e^+e^- \to s_\mu^+ s_\mu^-)}{d(\cos\theta)} = \frac{\pi\alpha^2\beta^3\sin^2\theta}{4s} ,$$

where β is the velocity of the s_μ and the factor of $\frac{1}{4}\sin^2\theta\,\beta^3$ is due to the spin-0 nature of the s_μ. The s_μ is assumed to decay rapidly to a muon and a massless photino isotropically in its rest frame. For light s_μ's, the residual muon pairs are mostly back-to-back. For heavier s_μ's (mass > 3 GeV/c^2), the two residual muons are in general acollinear and acoplanar. This is illustrated in Fig. 3, where the observed acoplanarity distribution is compared with expectations including a 7-GeV/c^2 s_μ. The predicted excess of events at large acoplanarity angles is clearly not supported by the data. The number of expected and observed events are shown in Fig. 4 as a function of the assumed mass of the s_μ. The horizontal line is the number of observed events with $\Delta\psi > 30°$. The dashed curve is the two-standard-deviation limit of the expected number of events, calculated assuming only statistical errors. The effect of systematic errors is negligible. Combined with previous experiments[11] which have excluded s_μ up to the τ mass (1.78 GeV/c^2), the present results exclude the existence of a s_μ with a mass < 13.8 GeV/c^2 at the 95% confidence level. Our result is also consistent with similar studies performed at PETRA.[12]

In conclusion, we have studied acollinear muon pair production in e^+e^- collision. The results are in good agreement with the QED predictions. The existence of a supersymmetric muon with a mass < 13.8 GeV/c^2 is excluded at the 95% confidence level.

ACKNOWLEDGMENTS

This work was supported in part by the U. S. Department of Energy under Contracts numbers DE-AC02-81ER40025 (CU), DE-AC03-76SF00515 (SLAC), and DE-AC02-76ER00881 (UW); by the U.S. National Science Foundation under Contracts numbers NSF-PHY-82-15133 (UH), NSF-PHY79-20020, NSF-PHY79-20821 (NU), and NSF-PHY80-06504 (UU); and by Istituto Nazionale di Fisica Nucleare, Italy.

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