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Experimental Test of Higher-Order QED and a Search for Excited Muon States*

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ABSTRACT

The processes $e^+e^-\to\mu^+\mu^-\gamma$ and $e^+e^-\to\mu^+\mu^-\gamma\gamma$ have been studied at $\sqrt{s}$=29 GeV with the MAC detector at PEP. Comparisons are made with QED theory, and limits for the production of excited muon states are presented. A large charge asymmetry is observed in the process $e^+e^-\to\mu^+\mu^-\gamma$. This asymmetry and the measured cross sections for both reactions are in good agreement with the predictions of QED.

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The processes $e^+e^-\to\mu^+\mu^-\gamma$ and $e^+e^-\to\mu^+\mu^-\gamma\gamma$ are appropriate for tests of higher-order quantum electrodynamics (QED) theory and a search for excited states of the muon. This paper presents the results of a study of these reactions with the MAC detector at PEP. The data reported here are based on an integrated luminosity of 30pb^{-1}, of which 28pb^{-1} were taken at $\sqrt{s}$=29GeV, the remainder at $\sqrt{s}$=28GeV.

There have been many theoretical discussions of the possibility that quarks and leptons are composed of more elementary constituents.[1] If quarks and leptons were composites, there would exist low-lying excited states of these particles. The high-precision measurements of the electron and muon anomalous magnetic moments have set an experimental constraint on the effect of these excited states.[2] A more direct search for these excited states can be provided by high-energy e^+e^- annihilation experiments. Such searches have been performed at ADONE,[3] SPEAR,[4] and more recently at PETRA.[5] This paper presents the results of a search for excited states of the muon (μ^*), assuming that the μ^* decays promptly via $\mu^*\to\mu\gamma$. If an excited muon existed, it could be produced by either $e^+e^-\to\mu^{*\pm}\mu^{*\mp}$ or $e^+e^-\to\mu^{*\pm}\mu^{\mp}$ depending on the μ^* mass. In the $\mu^*\mu^*$ process, the μ^* would presumably couple to the virtual photon in the same manner as the muon, except for a possible form factor. The $\mu^*\mu$ process could proceed via tensor coupling defined by the following interaction Lagrangian:[6]

$$L_{int} = \lambda e \bar{\Psi}_{\mu^*} \sigma_{\alpha\beta} \Psi_{\mu} F^{\alpha\beta} + h.c.,$$

where λ is a coupling constant and $F^{\alpha\beta}$ is the electromagmetic field tensor. If the μ^* is assumed to have spin $\frac{1}{2}$, the differential cross sections for these processes are given by

$$\frac{d\sigma}{d\Omega}(ee\to\mu^*\mu^*) = \frac{\alpha^2}{4s}\left|F(s)\right|^2 \beta\left[1+\cos^2\theta+(1-\beta^2)\sin^2\theta\right] , \qquad (1)$$

where β is the μ^* velocity and F(s) is the μ^* form factor, and

$$\frac{d\sigma}{d\Omega}(ee\to\mu^*\mu) = \lambda^2\alpha^2\frac{(s-M^2)^2}{s^3}\left[(s+M^2)-(s-M^2)\cos^2\theta\right] , \qquad (2)$$

where M is the μ^* mass. If the μ^* decays via $\mu^* \to \mu\gamma$, the $\mu^*\mu^*$ and $\mu^*\mu$ final states would be mixed with the higher-order QED processes $e^+e^-\to\mu^+\mu^-\gamma\gamma$ and $e^+e^-\to\mu^+\mu^-\gamma$, and therefore both final states should be compared to the predictions of QED.

A detailed description of the MAC detector has been given elsewhere[7]. Charged particles are analyzed in a central drift chamber consisting of 10 layers of drift wires inside a solenoid coil with a magnetic field of 5.7 kG, with momentum resolution $\Delta p/p \simeq 0.065\ p \sin\theta$. The polar angle acceptance is $17^0 \leq \theta \leq 163^0$. Photons are detected by calorimeters surrounding the solenoid coil in the form of a central hexagonal cylinder with planar end caps. These shower detectors consist of layers of lead (central) or steel (end caps) interspersed with proportional wire chambers. The energy and angular resolutions of the central (end cap) chambers are $\Delta E/E \simeq 20\%/\sqrt{E}$ $(45\%/\sqrt{E})$, $\Delta\phi\simeq0.8^0$ (2.0^0), $\Delta\theta\simeq1.3^0$ (1.5^0), respectively. The electromagnetic calorimeters are surrounded by hadron calorimeters, which consist of proportional wire chambers interspersed between steel plates totaling 5 absorption lengths. These steel plates are magnetized at 17 kG and surrounded by drift chambers to form a toroidal spectrometer for muons. The charged tracks reconstructed in the central drift chamber are extrapolated to the electromagnetic and hadron calorimeters and the calorimeter information associated with the charged tracks is used for particle identification. The combination of inner and outer drift chamber systems is used to determine the muon charge.

$\mu\mu\gamma$ final state - The event selection criteria required: 1) two charged tracks reconstructed to the interaction vertex by the central drift chamber, with an acollinearity angle greater than 10 degrees; 2) both charged particles associated with electromagnetic shower energy less than 1.4 GeV (the minimum ionizing peak is at 0.3 GeV) with at least one of the two particles penetrating all the hadron calorimeter layers; 3) one neutral electromagnetic shower (not associated with a charged track) with energy greater than 1 GeV; and 4) the three particle system to fit the $e^+e^-\to\mu^+\mu^-\gamma$ kinematic four constraint hypothesis with a confidence level greater than 0.5% and the invariant mass of the dimuon system to be greater than 1.5 GeV. Criterion 1) rejects collinear events such as Bhabha, mu-pairs, and cosmic rays, and criterion 2) rejects radiative Bhabha events. Criteria 3) and 4) discriminate against $e^+e^-\to e^+e^-\mu^+\mu^-$ and $e^+e^-\to\tau^+\tau^-$ events. 170 events satisfy these requirements. From Monte Carlo studies it is estimated that 2.6 $e^+e^-\to e^+e^-\mu^+\mu^-$ and 3.3 $e^+e^-\to\tau^+\tau^-$ events remain as background in the sample. The Monte Carlo program of Berends and Kleiss[8] was used to calculate the QED prediction for $e^+e^-\to\mu^+\mu^-\gamma$ to order α^3. The events generated by the program were then put through the MAC detector simulation program[9] to take account of the detector acceptance and the event selection criteria. The QED prediction is 176 events.

Fig. 1 shows the muon-photon invariant mass distribution (2 entries per event) with a solid curve representing the QED prediction. Events from single μ^* production would appear as a narrow peak in this distribution (the mass resolution is about 0.3 GeV/c^2). The observed events are in good agreement with the QED prediction.[10] Fig. 2(a) shows the 90% C.L. upper limit for the μ^* production cross section $\sigma_{\mu^*\mu}$ relative to the muon-pair cross section $\sigma_{\mu\mu}$, as a function of the μ^* mass. The acceptance for μ^* production was calculated by a Monte Carlo method assuming Eq. (2). The limit on μ^* production is less than 0.2% of the point cross section. From Eq. (2) the limit can also be expressed in terms of λ^2, as shown in Fig. 2(b).

Fig. 3 shows the combined μ^+ and μ^- angular distribution as the quantity $N_{\mu^+}(\cos\theta)+N_{\mu^-}(-\cos\theta)$ plotted versus $\cos\theta$, with θ measured relative to the e+ beam direction. A substantial asymmetry about $\cos\theta=0$ is evident. The average charge asymmetry, defined as

$$\bar{A} \equiv \frac{N_{\mu^+}(\theta<\tfrac{1}{2}\pi) + N_{\mu^-}(\theta>\tfrac{1}{2}\pi) - N_{\mu^+}(\theta>\tfrac{1}{2}\pi) - N_{\mu^-}(\theta<\tfrac{1}{2}\pi)}{N_{\mu^+} + N_{\mu^-}} ,$$

is $\bar{A}$ = (-24.7 ± 5.3)%. Such an asymmetry is expected from QED due to the interference between amplitudes corresponding to the initial and final state radiation of a hard photon.[11] One of the amplitudes represents Compton scattering of a photon from a muon, a process not accessible by direct measurement. The asymmetry due to QED becomes quite large for the hard photon case compared to the relatively small value (≃2-3%) expected for the collinear $\mu^+\mu^-$ final state. The angular distribution predicted by the QED Monte Carlo is shown as the solid curve in Fig. 3 and yields a charge asymmetry $\bar{A}$ = (-21.1 ± 1.3)%, where the error is due to the statistical uncertainty of the Monte Carlo calculation. An additional contribution to the asymmetry is expected from interference with the weak interaction terms, and has been calculated[12] to be $\bar{A} \simeq -2\%$. The measured value is in good agreement with these predictions.

<u>$\mu\mu\gamma\gamma$ final state</u> - The event selection criteria are as described above for the $\mu\mu\gamma$ final state except that: (1) one more photon with $E_\gamma > 1$ GeV is required; (2) the angle between a muon and a photon or between the two photons must be greater than 10 degrees; and (3) the four particle system must fit the $\mu^+\mu^-\gamma\gamma$ hypothesis. 15 events satisfy these requirements, and the sample is estimated to contain 3 background events coming from the $e^+e^-\to\tau^+\tau^-$ final state. The QED prediction is 9 events, as determined from the Monte Carlo program of Rek and Schmitt[13], which evaluates the α^4-order contribution to hard-photon production. Fig. 4 shows the scatter plot of $\mu\gamma$ mass combinations for these events (2 entries per event). If μ^*'s were pair-produced, the corresponding events would form a cluster around a point on the 45° line, within the mass resolution indicated by the dashed lines. No indication of μ^* production is observed, and the scatter plot and other kinematic distributions are consistent with the QED predictions. Fig. 2(a) shows the 90% C.L. upper limit on $\sigma_{\mu^*\mu^*}$ relative to the point cross section $\sigma_{\mu\mu}$ modified by the threshold factor $\frac{1}{2}(3\beta-\beta^3)$, as a function of the μ^* mass, together with the limit for the $\mu^*\mu$ final state. The acceptance was calculated by a Monte Carlo method assuming Eq. (1). If the μ^* form factor is assumed to be 1.0, μ^* production is excluded in the mass region between 1.0 and 14.5 GeV/c^2 at 90% confidence level.

In conclusion, a search for excited muon states has been carried out by detecting $ee\to\mu\mu\gamma$ and $\mu\mu\gamma\gamma$ final states. No evidence for excited muon production has been found. Total cross sections and various kinematic variables, including the charge asymmetry of the $\mu\mu\gamma$ final state, agree with the predictions of QED.

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Figure Captions

Fig. 1. The $\mu\gamma$ invariant mass distribution for the $\mu\mu\gamma$ final state. The solid curve is the QED prediction.

Fig. 2. (a) The 90% C.L. upper limit on the cross section, relative to the point cross section, for production of $\mu^*\mu^*$ (solid curve) and $\mu^*\mu$ (dashed curve) final states. (b) 90% C.L. upper limit on λ^2 for the $\mu\mu\gamma$ final state.

Fig. 3. Polar angle distribution of muons for the $\mu\mu\gamma$ final state. The solid curve is the QED prediction.

Fig. 4. Scatter plot of the invariant masses of $\mu^+\gamma$ and $\mu^-\gamma$ combinations for the $\mu\mu\gamma\gamma$ final state. Dashed lines indicate a range of two standard deviations of the $\mu\gamma$ mass resolution about the 45^0 line.

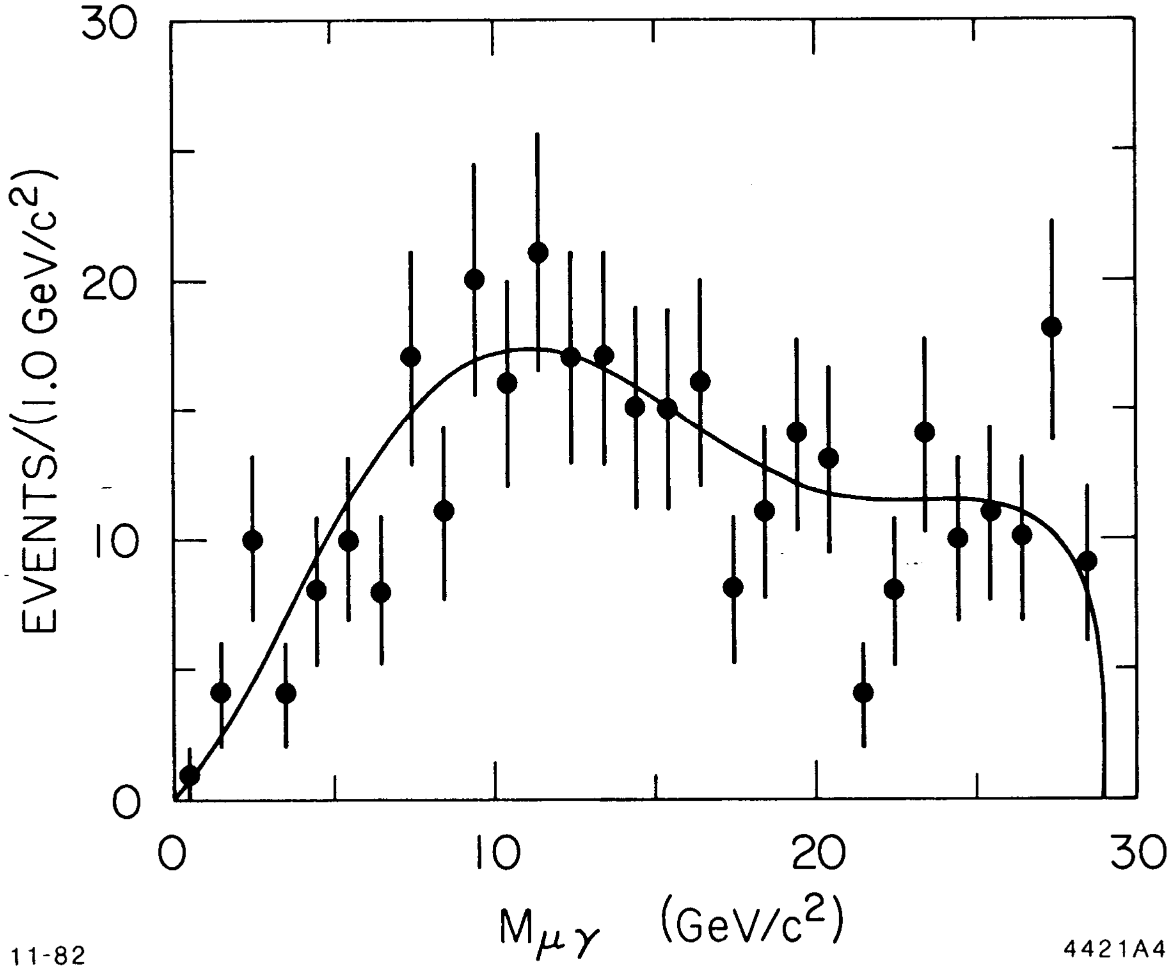
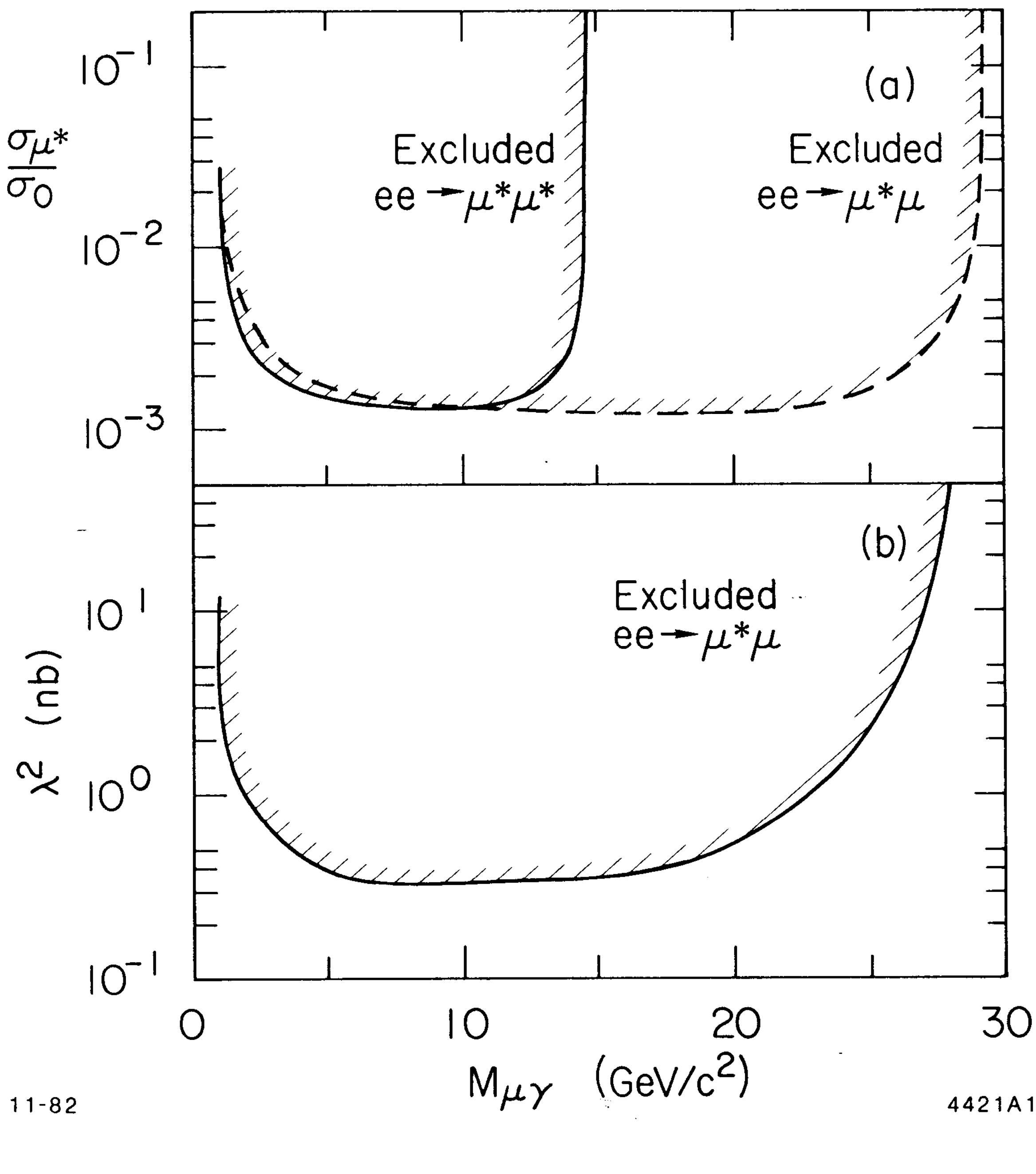


Fig. 1



10^{-1}
10^{-2}
10^{-3}
$\frac{\sigma_{\mu^*}}{\sigma_0}$
(a)
Excluded
ee → μ*μ*
Excluded
ee → μ*μ
(b)
Excluded
ee → μ*μ
10^{1}
10^{0}
10^{-1}
λ^2 (nb)
0
10
20
30
$M_{\mu\gamma}$ (GeV/c^2)
11-82
4421A1

Fig. 2

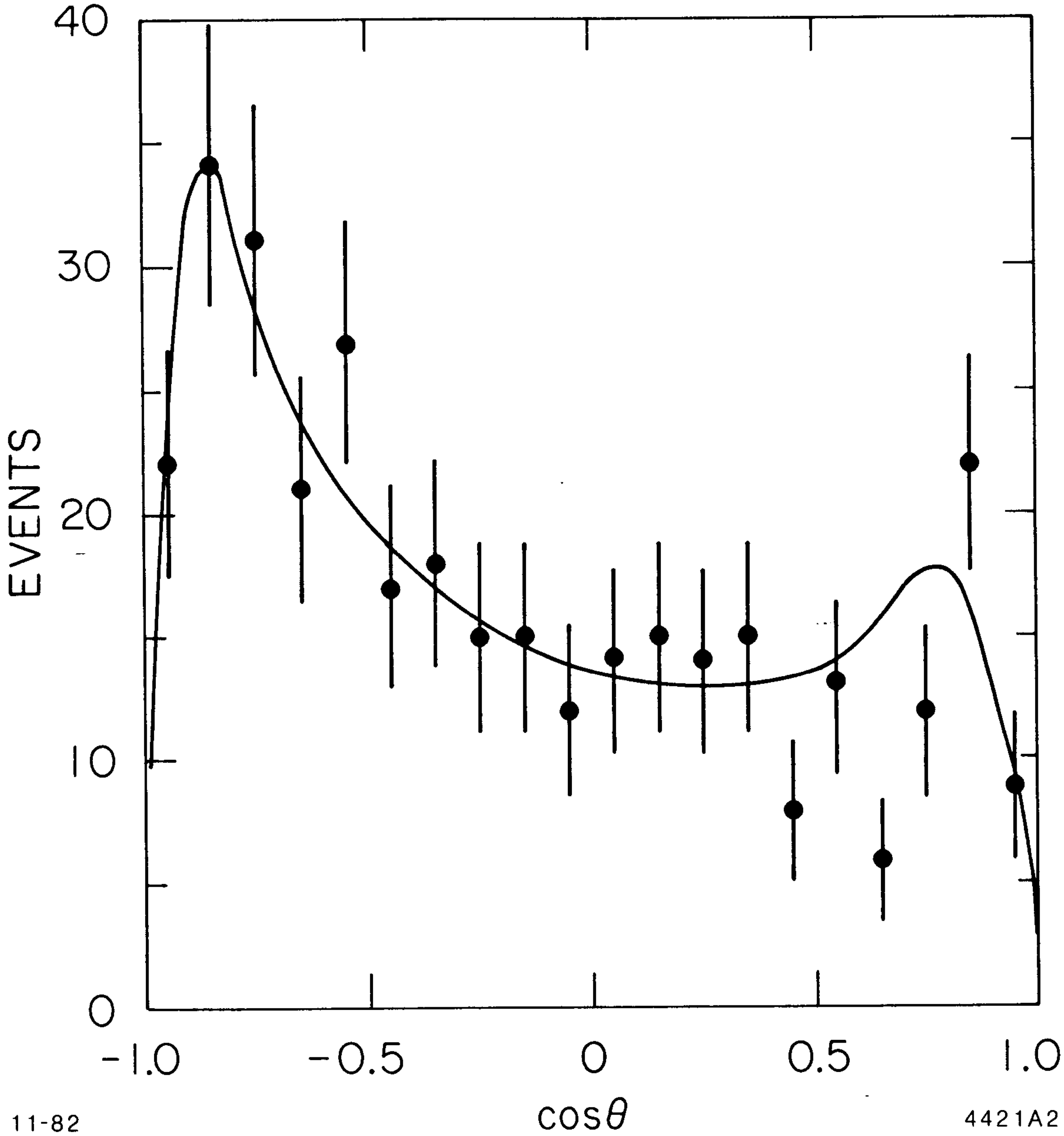


Fig. 3

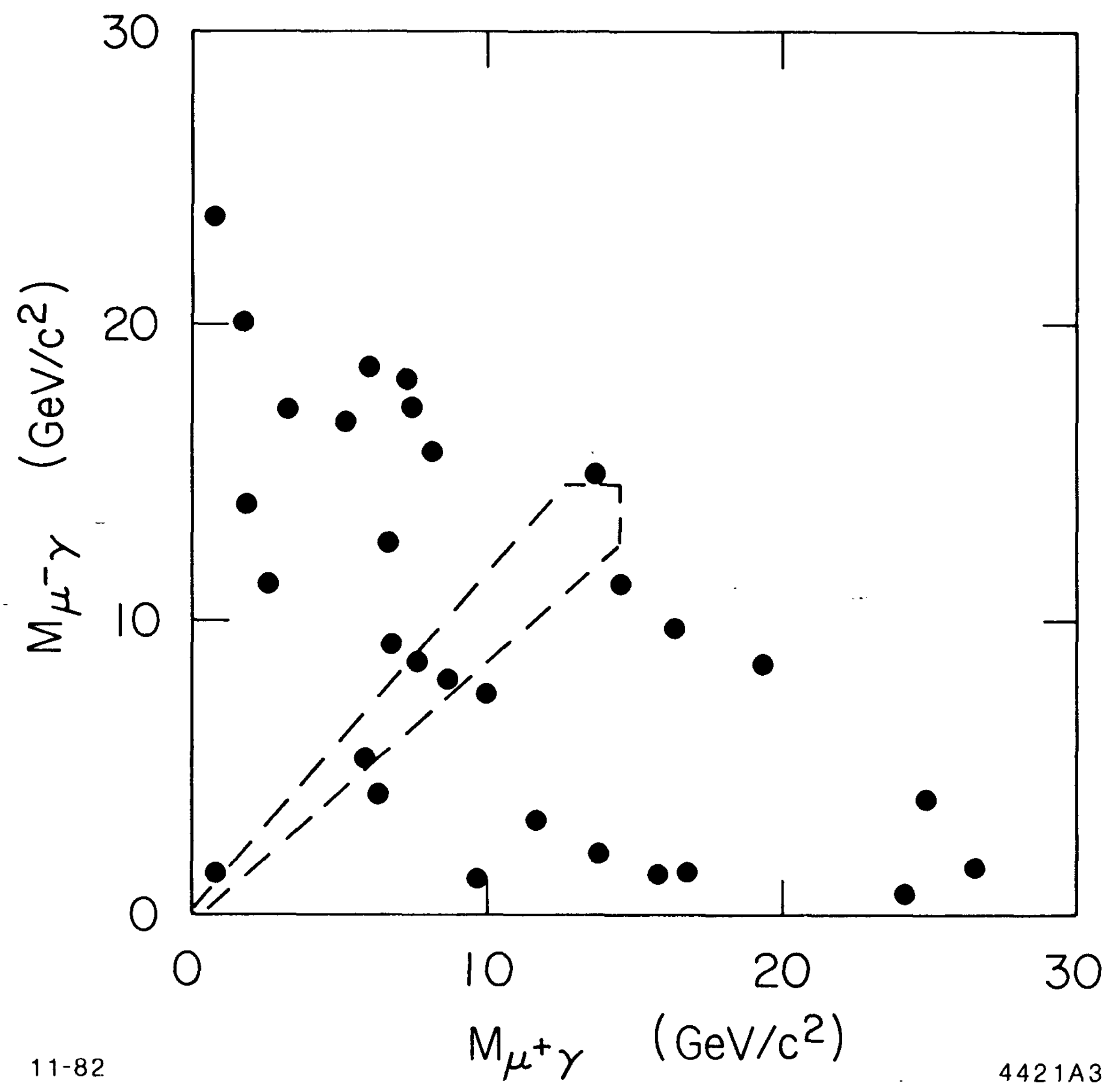

30
20
10
0
0
10
20
30
$M_{\mu^- \gamma}$ (GeV/c^2)
$M_{\mu^+ \gamma}$ (GeV/c^2)
11-82
4421A3

Fig. 4