SLAC-PUB-1501
LBL-3385
November 1974
(T/E)

MEASUREMENT OF $e^+e^- \to e^+e^-$ AND $e^+e^- \to \mu^+\mu^-$ AT SPEAR*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, R. F. Schwitters, and F. Vannucci

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, G. H. Trilling, J. S. Whitaker, and J. E. Zipse

Lawrence Berkeley Laboratory and Department of Physics
University of California, Berkeley, California 94720

ABSTRACT

The reactions $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$ have been measured at center-of-mass energies 3.0, 3.8, and 4.8 GeV and production angles of $50^\circ < \theta < 130^\circ$ over all azimuthal angles. Agreement with QED is excellent. New limits for cutoff parameters in QED breakdown models are given.

(Submitted to Phys. Rev. Letters.)

---

*Work supported by the U. S. Atomic Energy Commission.

†Laboratoire de l'Accélérateur Linéaire, Centre d'Orsay de l'Université de Paris, 91 Orsay, France.

We report results from an experiment performed at the SLAC positron-electron storage ring (SPEAR I) to test with high precision the validity of quantum electrodynamics (QED) at large momentum transfers for the reactions

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

$$e^+e^- \rightarrow \mu^+\mu^- \tag{2}$$

Data were collected at center-of-mass energies (E_{cm}) of 3.0, 3.8, and 4.8 GeV. A solenoidal magnetic spectrometer was used to measure angles, momenta and charges of the final state particles, resulting in a particularly stringent test of QED. While QED field theory has successfully explained results of previous experiments[1] on these reactions, ultimately deviations from QED are expected to occur at sufficiently large momentum transfers. Such deviations could be caused by photon propagator modifications resulting from the recently observed large cross section for the reaction $e^+e^- \rightarrow$ hadrons,[2] or from the exchange of a neutral heavy boson like that required in the unified theories of weak and electromagnetic interactions, or from an intrinsic breakdown of QED itself.

SPEAR has two e^+e^- collision regions, each having an overlap size ($\sigma_x, \sigma_y, \sigma_z$) of approximately (1.5, 0.09, 20 E_{cm}) mm. The apparatus for this experiment, shown in Fig. 1, was positioned centrally about one of the interaction regions (IR), and subtended $0.65 \times 4\pi$ steradians. The 3-m diameter × 3-m long coil produced a nominal 4-kG field coaxial with the beam direction (z-axis). Particles entering the detector from the IR pass through a 0.15-mm stainless steel vacuum chamber; an inner trigger counter (3-mm scintillator) for reducing cosmic-ray background; 4 sets of concentric cylindrical wire spark chambers, each set having one gap with wires at $\pm 2^{\circ}$ and another at $\pm 4^{\circ}$ with respect to the z axis; an outer trigger counter having 48 2.5-cm thick plastic scintillation counters, which provide time-of-flight (TOF) information with a resolution of

±0.5 nsec; the aluminum coil of 9 cm thickness; a cylindrical array of 24 lead-scintillator shower counters (5 radiation lengths) for electron identification; the 20-cm thick iron return yoke of the magnet which also serves as a hadron filter; and finally two gaps of wire spark chambers which aid in muon-hadron separation. Iron endcaps provide a completely enclosed magnetic field, uniform to 3 percent over the active solid angle. The full azimuth is used while the acceptance in polar angle θ was 50° to 130°, limited by the outer trigger counters. A hardware trigger selected events having two or more charged particles by requiring occurrence of signals from the inner trigger counter and at least two outer trigger counter/shower counter combinations during the beam crossing time.

The analysis programs constructed helical tracks from the cylindrical chamber information, and determined the corresponding TOF and shower pulse height for each track. Events from reactions (1) and (2) were separated from cosmic particles, background, and hadronic events by requiring that there be only two tracks which originated from an IR fiducial volume of 4-cm radius by 80-cm length, were oppositely charged, had equal TOF within ±3 nsec, were collinear to $\leq 10^{\circ}$, and had momenta $p \geq E_{cm}/4$. The latter two cuts eliminated e^+e^- or $\mu^+\mu^-$ events that radiated strongly and suppressed the processes $e^+e^- \rightarrow e^+e^-e^+e^-$ and $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$. Separation of reactions (1) and (2) was accomplished by using shower counter pulse-height data, as shown in Fig. 2. A single cut at 70 clearly separates the e^+e^- from the $\mu^+\mu^-$ final states. Although hadron pairs (for example $\pi^+\pi^-$) could appear in the $\mu^+\mu^-$ class, a study of the muon chamber information indicates no significant contamination from this source.

The only significant hardware correction came from the shower-counter trigger, which was 94% to 98% efficient (depending on θ) for the $\mu^{\pm}$ signals ($\approx$ 100% for $e^{\pm}$). No background subtraction was required, since we saw no QED candidates in noncolliding beam runs, comprising about 10% of the running time.

Using QED cross sections with radiative terms according to Berends et al.,[3] we normalized to the total e^+e^- counts within the interval $|\cos\theta_+| < 0.6$, and made comparisons between corrected counts and theory for the shape of the e^+e^- angular distribution, for the $\mu^+\mu^-$ distribution and the $\mu^+\mu^-/e^+e^-$ ratio. Agreement was good at all energies. Figure 3 shows one angular distribution. Total counts over $|\cos\theta_+| < 0.6$, and the ratio of observed to expected $\mu^+\mu^-$ events were:

E_{cm} (GeV)	3.0	3.8	4.8
e^+e^- counts	7671	13419	15788
$\mu^+\mu^-$ counts	563	1097	1241
$\left(\frac{\text{expt}}{\text{QED}}\right)_{\mu^+\mu^-}$	0.95 ±0.04	1.05 ±0.03	1.01 ±0.03

To establish limits on QED validity, we determine the limiting values that the parameter Λ can have in a modified photon propagator model.[4] This is equivalent to modifying the QED amplitudes with form factors which we parameterize as

$$F(Q^2) = \left(1 \mp \frac{Q^2}{\Lambda_\pm^2}\right)^{-1} \approx 1 \pm \frac{Q^2}{\Lambda_\pm^2} \qquad (3)$$

where Q^2 is the photon four-momentum transfer and the +/- sign is used for establishing limits in Λ for positive or negative metrics. Our e^+e^- angular span

is sufficiently large that separate limits can be extracted for space-like (Λ_S) and time-like (Λ_T) photons, although different Λ_S and Λ_T would violate crossing symmetry as well as QED. The modified cross section for $e^+e^- \to e^+e^-$ is

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2s}\left[\frac{q'^4 + s^2}{q^4}\,|F_S|^2 + \frac{2q'^4}{q^2 s}\,\mathrm{Re}(F_S F_T^*) + \frac{q'^4 + q^4}{s^2}\,|F_T|^2\right], \qquad (4)$$

where $q^2 = -s\sin^2\theta/2$; $q'^2 = -s\cos^2\theta/2$; $s = E^2_{cm}$; $F_S = 1 \pm q^2/\Lambda^2_{S\pm}$; and $F_T = 1 \pm s/\Lambda^2_{T\pm}$. For $e^+e^- \to \mu^+\mu^-$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left[1 + \cos^2\theta + (1-\beta^2_\mu)\sin^2\theta\right]|F_T|^2 \quad . \qquad (5)$$

By simultaneously fitting both the $\mu^+\mu^-$ and e^+e^- data with the same Λ_T parameter (i.e., assuming μ-e universality) a much more sensitive test of QED can be made than is possible for the e^+e^- data alone.

As an alternate QED modification method, one can insert form factors at the $ee\gamma$ and $\mu\mu\gamma$ vertices. This formulation is more suitable for establishing limits on the point structure of electrons and muons, as well as on μ-e universality. In a similar way, we parametrize the electron and muon form factors by $F_{e,\mu}(Q^2) = 1 \pm Q^2/\Lambda^2_{e,\mu}$.

The various cutoff constants $1/\Lambda^2$ were found by fitting the $\mu^+\mu^-$ and/or e^+e^- angular distributions to the modified QED cross sections normalized to the total e^+e^- counts within $|\cos\theta| \leq 0.6$ (the normalization is a function of Λ also). Table I gives the results of the fits, with the corresponding lower limits for $\Lambda_\pm$ (95% confidence level) for the various breakdown models. This is the first time that separate space- and time-like limits have been established for process (1). The assumption of a single form factor for both space-like and time-like photons gives cutoffs $\Lambda_+ > 35$ GeV and $\Lambda_- > 47$ GeV, which are considerably larger than the previous highest limits ($\Lambda_+ > 14.5$ GeV, $\Lambda_- > 23.6$ GeV) set by Beron et al.[1]

No deviation of either the electron or muon form factor from unity has been observed, the cutoff parameters being always larger than 16 GeV. Our limit $\Lambda_{\mu e}$ on μ-e universality, defined by $1/\Lambda_{\mu e}^2 \equiv 1/\Lambda_\mu^2 - 1/\Lambda_e^2$, is $\Lambda_{\mu e+} > 13$ GeV and $\Lambda_{\mu e-} > 15$ GeV determined from the (correlated) difference between $1/\Lambda_\mu^2$ and $1/\Lambda_e^2$ from Table I.

We wish to acknowledge the many people who contributed to the construction of SPEAR and the magnetic detector, and the operators for running the storage ring. Their efforts were essential to the success of this experiment.

TABLE I

Weighted averages over the three energies of the fitting parameters and 95% cutoff limits established from the e^+e^- data, from the $\mu^+\mu^-$ data together with e^+e^-, for QED breakdown models with (a) separate form factors for space- and time-like photons, (b) same form factors for space- or time-like photons, and (c) separate form factors at the $ee\gamma$ and $\mu\mu\gamma$ vertices.

Data Used	Model	Fitted Parameters (Λ in GeV)	Λ at 95% C.L. (GeV) pos. metric	Λ at 95% C.L. (GeV) neg. metric
ee only	a	$1/\Lambda_S^2 = 0.0008 \pm 0.0022$ $1/\Lambda_T^2 = 0.0013 \pm 0.0031$ correl. coeff. = 0.82	$\Lambda_{S+} > 15$ $\Lambda_{T+} > 13$	$\Lambda_{S-} > 19$ $\Lambda_{T-} > 16$
	b	$1/\Lambda^2 = 0.0007 \pm 0.0022$	$\Lambda_+ > 15$	$\Lambda_- > 19$
$\mu\mu$ and ee	a	$1/\Lambda_S^2 = 0.0003 \pm 0.0013$ $1/\Lambda_T^2 = 0.0001 \pm 0.0005$ correl. coeff. = 0.23	$\Lambda_{S+} > 21$ $\Lambda_{T+} > 33$	$\Lambda_{S-} > 23$ $\Lambda_{T-} > 36$
	b	$1/\Lambda^2 = 0.0002 \pm 0.0004$	$\Lambda_+ > 35$	$\Lambda_- > 47$
	c	$1/\Lambda_e^2 = 0.0004 \pm 0.0011$ $1/\Lambda_\mu^2 = 0.0014 \pm 0.0021$ correl. coeff. = -0.97	$\Lambda_{e+} > 21$ $\Lambda_{\mu+} > 27$	$\Lambda_{e-} > 19$ $\Lambda_{\mu-} > 16$

REFERENCES

1. B. L. Beron et al., Phys. Rev. Letters 33, 663 (1974); H. Newman et al., Phys. Rev. Letters 32, 483 (1974); M. Bernardini, Phys. Letters 45B, 510 (1973); B. Borgia et al., Letters Nuovo Cimento 3, 115 (1972); V. Alles-Borelli et al., Nuovo Cimento 7A, 330 (1972).
2. G. Tarnopolsky et al., Phys. Rev. Letters 32, 432 (1974); J.-E. Augustin et al., SLAC-LBL-SPEAR Magnetic Detector Group (to be published).
3. F. A. Berends, K. J. F. Gaemers and R. Gastmans, Nucl. Phys. B68, 541 (1974) and Nucl. Phys. B63, 381 (1973). We are indebted to these authors for supplying to us their computer program. Radiative corrections were -0.14 (-0.07), -0.13 (-0.06), and -0.12 (-0.03) for e^+e^- ($\mu^+\mu^-$) at $\cos\theta_+ = -0.5$, 0, and 0.5, respectively.
4. S. D. Drell, Ann. Phys. 4, 75 (1958); T. D. Lee and G. C. Wick, Nucl. Phys. B9, 209 (1969).

FIGURE CAPTIONS

1. End view of the solenoidal magnetic detector.
2. Distribution of the sum of the shower counter pulse heights for collinear events.
3. Angular distribution of positive prongs for $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$ at $E_{cm} = 4.8$ GeV. The histograms give the observed counts, while the curves are QED normalized to total e^+e^- counts within $|\cos\theta_+| \leq 0.6$.

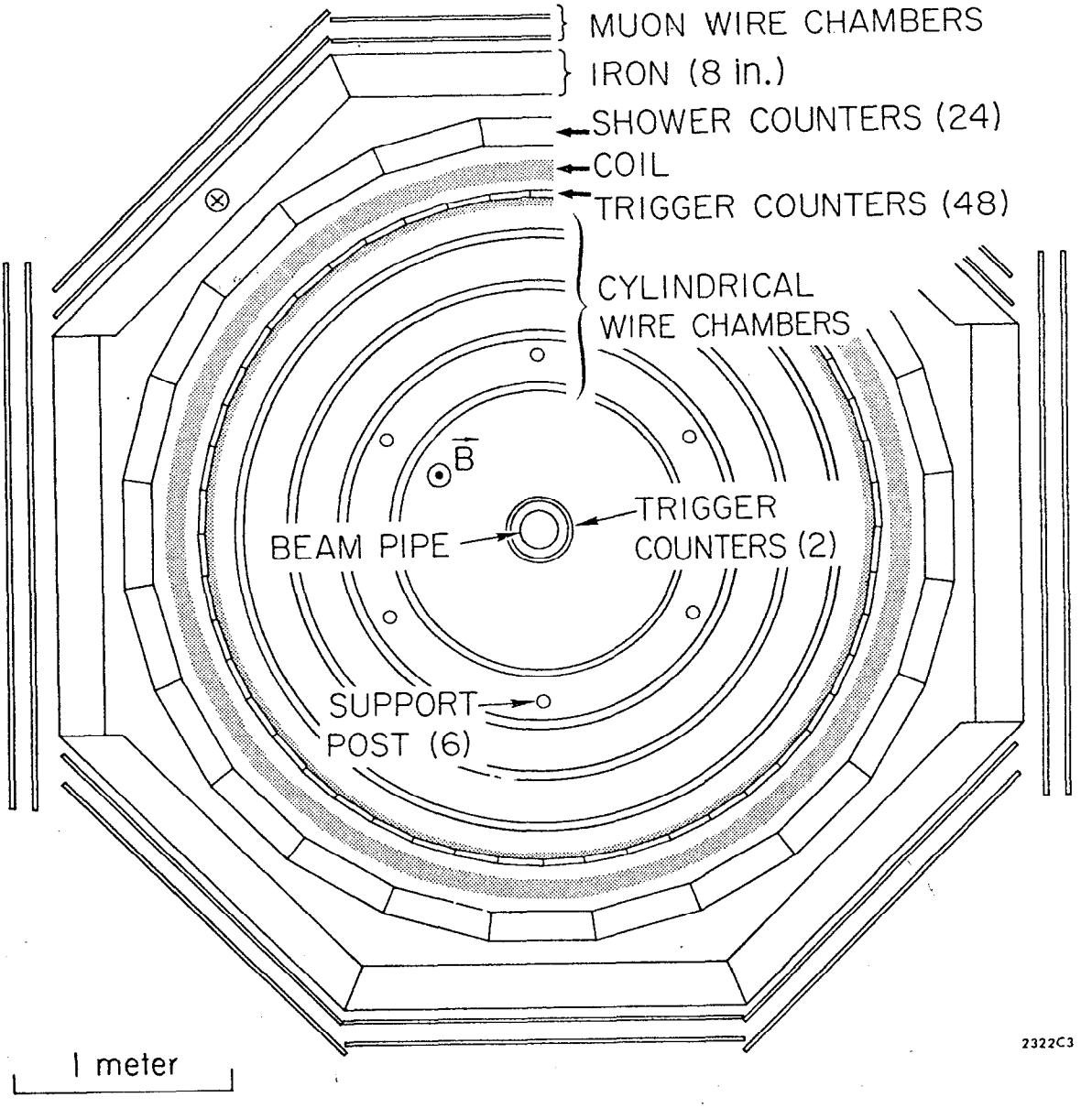
MUON WIRE CHAMBERS
IRON (8 in.)
SHOWER COUNTERS (24)
COIL
TRIGGER COUNTERS (48)
CYLINDRICAL
WIRE CHAMBERS
B
TRIGGER
COUNTERS (2)
BEAM PIPE
SUPPORT
POST (6)
2322C3
1 meter

Fig. 1

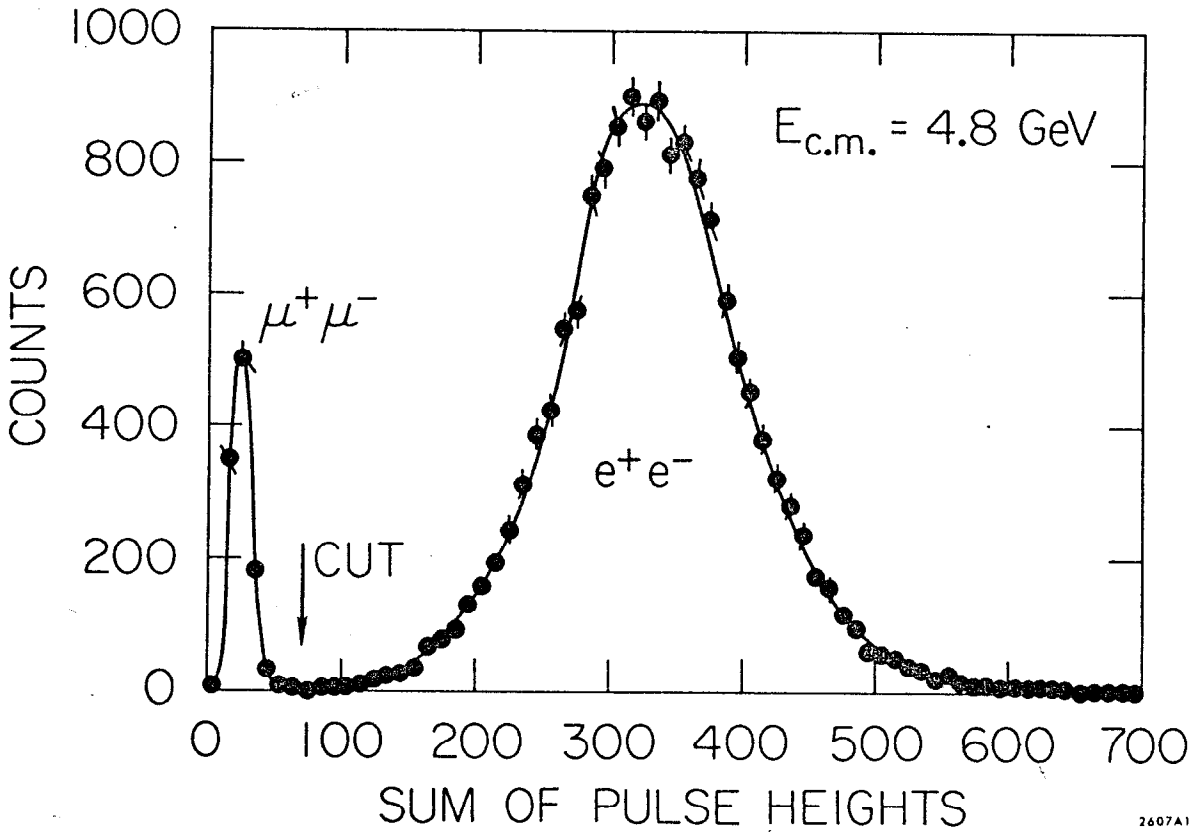
1000
800
600
400
200
0
COUNTS
$E_{c.m.}$ = 4.8 GeV
$\mu^+\mu^-$
e^+e^-
CUT
0
100
200
300
400
500
600
700
SUM OF PULSE HEIGHTS
2607A1

Fig. 2

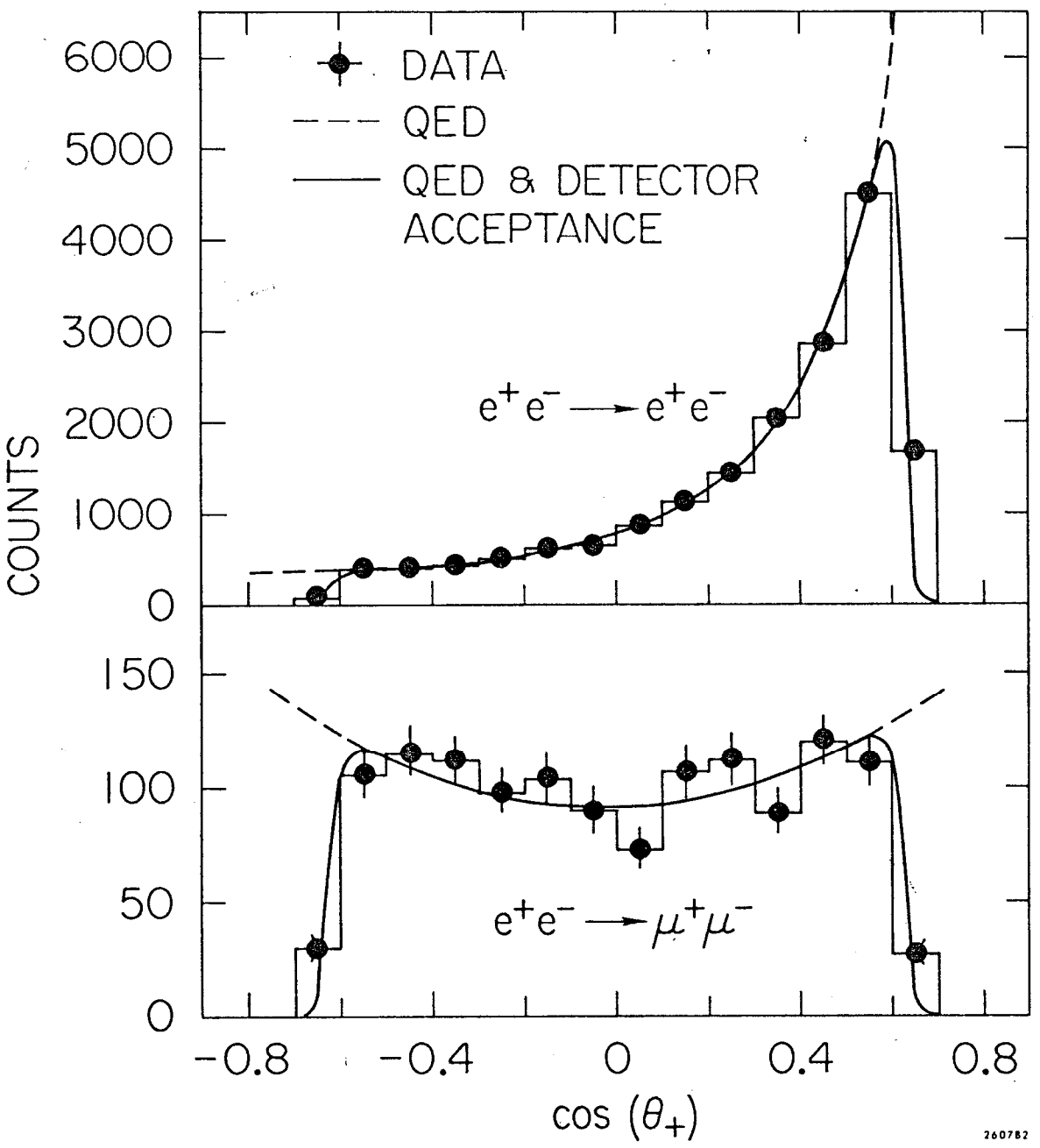
DATA
QED
QED & DETECTOR ACCEPTANCE
$e^+e^- \rightarrow e^+e^-$
$e^+e^- \rightarrow \mu^+\mu^-$
COUNTS
6000
5000
4000
3000
2000
1000
0
150
100
50
0
-0.8
-0.4
0
0.4
0.8
cos (θ_+)
260782

Fig. 3