# Measurements of the reaction $e^+e^- \to \mu^+\mu^-$ at center-of-mass energies in the range 6.2–7.4 GeV

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Measurements of the cross section for the muon-pair-annihilation reaction $e^+e^- \to \mu^+\mu^-$, relative to Bhabha scattering at 4°, are reported at center-of-mass energies in the range 6.2–7.4 GeV. These measurements provide a fundamental test of quantum electrodynamics (QED) for timelike values of the invariant four-momentum transfer $q^2$ as high as 54.8 $(\mathrm{GeV}/c)^2$, which in this reaction is carried by the photon propagator. The results are in agreement with predictions of QED

Recent measurements of cross sections for the reactions $e^+e^- \to e^+e^-$ (Ref. 1) and $e^+e^- \to \gamma\gamma$ (Ref. 2) at center-of-mass energies close to 7.4 GeV have been shown, by the authors of the present paper, to be in agreement with those predicted by the theory of quantum electrodynamics (QED). The apparatus used to obtain these results was also designed to detect the reaction $e^+e^- \to \mu^+\mu^-$ and in this way to provide, simultaneously, a third basic test of QED. Whereas in the reactions $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$, at large scattering angles, the invariant four-momentum transfer $q^2$ is dominantly spacelike and carried respectively by photon and electron propagators, in the reaction $e^+e^- \to \mu^+\mu^-$ $q^2$ is purely timelike and carried by a photon propagator. For these reasons, the muon-pair-annihilation reaction provides a uniquely different test of QED. The present experiment was carried out at the electron-positron storage ring SPEAR-II at the Stanford Linear Accelerator Center at center-of-mass energies in the range 6.2–7.4 GeV. The cross section for $e^+e^- \to \mu^+\mu^-$ was measured in one apparatus at angles close to 90° relative to that for Bhabha scattering ($e^+e^- \to e^+e^-$) at very small angles (~4°) in an independent apparatus, or luminosity monitor. At the very small angles only relatively small values of $q^2$ are involved and the validity of QED is assured. For the $e^+e^- \to \mu^+\mu^-$ events detected at large angles the timelike values of $q^2$ involved are in the range 38.4–54.8 $(\mathrm{GeV}/c)^2$. In terms of integrated luminosity, the fractions of the total data accumulated at center-of-mass energies of 6.2, 7.0, and 7.4 GeV were 20, 12, and 68% respectively.

The apparatus at 90° consisted of two identical spectrometers mounted in a collinear configuration about the beam interaction region. Throughout the experiment these spectrometers were oriented at an azimuthal angle of 45° relative to the plane of the circulating beams in order to eliminate any influence on the measured cross sections of the transverse beam polarization at SPEAR-II.[3] A drawing of the two spectrometers is shown in Fig. 1. Each spectrometer contains a 20-radiation-length thick NaI(Tl) crystal 30 in. in diameter, preceded by three inner multiwire proportional chambers (MWPC's) and a plastic scintillator aperture counter. Following the NaI(Tl) crystal, each spectrometer also contains a fourth MWPC, a 16-in.-thick solid iron magnet of toroidal geometry, an array of four plastic scintillator timing counters and a fifth outer MWPC. Each MWPC provides

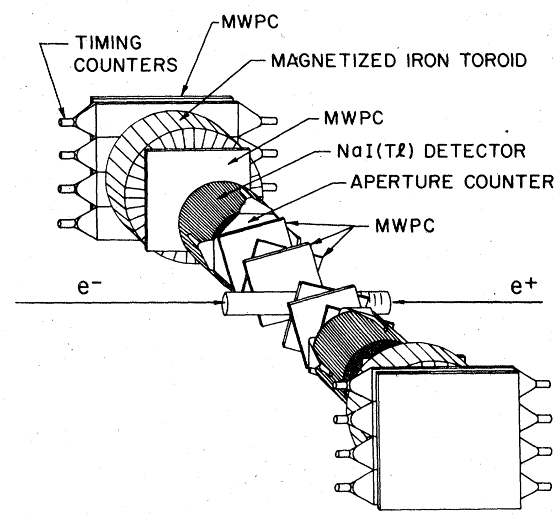


FIG. 1. A drawing of the two spectrometers used at 90°. The sensitive areas of the three sizes of MWPC's used in each spectrometer are 25.6 in. 25.6 in., 38.4 in.×38.4 in., and 51.2 in.×51.2 in. respectively.

 

coordinate information in two orthogonal directions and is oriented with respect to the common axis of the spectrometers as indicated in Fig. 1. The magnets, in conjunction with the NaI(Tl) crystals, impose a severe range requirement (~830 MeV/$c$ for muons) on the detected particles and, with the spatial information provided by the MWPC's, verify that the momenta of the detected muons are consistent with the large momenta expected for the reaction $e^+e^- \to \mu^+\mu^-$. The timing counters measure the time of detection of muons relative to the crossing of the beams and provide a powerful means of rejecting cosmic-ray muons. The electronic signature for an event of the type $e^+e^- \to \mu^+\mu^-$ required signals from the aperture and timing counters in each spectrometer in coincidence with the crossing of the beams. Upon receipt of this signature the coordinate information from all the MWPC's and the pulse heights and times of occurrence of the pulses in all the NaI(Tl) crystals and plastic-scintillator counters were recorded.

The absolute luminosity of the storage ring was monitored in an independent apparatus, or luminosity monitor, of the type described by Crawford *et al.*[4] but whose design was optimized for use at SPEAR-II and which contained diagnostic features not available to Crawford *et al.* The performance of this monitor has been described recently by the authors of the present paper,[1] who conclude that the systematic uncertainty on the number of Bhabha events detected does not exceed ±0.5%. A sketch of this new monitor is shown in Fig. 2. It consists of four quadruplets of counters symmetrically located with respect to the beam interaction region. Bhabha events are recognized by a coincidence between all four counters in any quadruplet and the opposite $C,S$ pair. The geometrical acceptance for such events is determined by the small counters $P$. The sum of the four possible signatures of this type, which is very insensitive to the size and to all possible movements of the luminous region, is used as the measure of luminosity. A detailed account of the performance of this monitor is in preparation.[5]

Candidate events for the reaction $e^+e^- \to \mu^+\mu^-$ were selected by requiring the deposition of a minimum of 50 MeV in each NaI(Tl) crystal, the occurrence of fired wires in at least three of four inner MWPC coordinate planes in each spectrometer (only the first and third of the inner MWPC's participated in this requirement), the detection of the event in both aperture counters within ±30 nsec of the beam crossing, and the measurement of a time difference between the detection of the event in the two timing counters of no more than 8 nsec (the expected time difference for cosmic-ray events is ~13 nsec). All candidate events were reconstructed and displayed for inspection on a graphic terminal. As necessary, an interactive software system was employed to edit the data from the small MWPC's in order to complete the track reconstruction. Events were not accepted at this stage if two or more charged particles were found to emerge from the luminous region in either spectrometer. Subsequently, events were also rejected if the two reconstructed tracks displayed an acollinearity angle larger than 15° or if the reconstructed tracks did not intersect the planes of the respective timing counters within a circular aperture 51 in. in diameter. This aperture diameter was chosen so that a negligible number of events is lost from the physical aperture provided by the timing counters due to either multiple scattering in the NaI(Tl) crystals or in the magnets or because of the radial magnetic deflection.

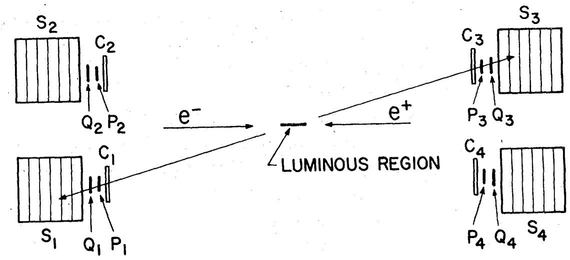


FIG. 2. A schematic diagram illustrating the operating principle of the luminosity monitor. The lead-scintillator shower counters $S$ have an energy resolution of 25% full width at half maximum and were operated at a trigger threshold of 0.7 GeV.

Figure 3 shows, at a center-of-mass energy of 7.4 GeV, the correlation between the average distance of the closest approach of the reconstructed tracks to the orbit of the circulating beams and the time difference between the pulses observed in the timing counters for $e^+e^- \to \mu^+\mu^-$ candidate events which satisfy all of the above criteria. All of the events in this plot display a small relative timing

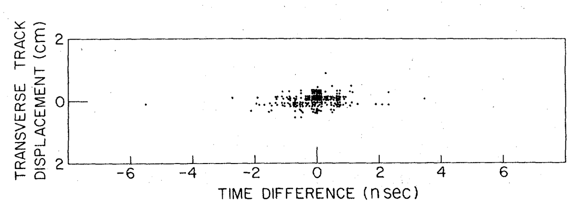


FIG. 3. Scatter plot for 210 $e^+e^- \to \mu^+\mu^-$ candidate events at a center-of-mass energy of 7.4 GeV showing the average transverse distance of the muon tracks from the orbit of the circulating beams versus the time difference between the detection of the event in the two timing counters.

TABLE I. A summary of the observed and expected numbers of events. The observed, unweighted numbers of events are 210, 53, and 111 at center-of-mass energies of 7.4, 7.0 and 6.2 GeV respectively.

| | | | |
|---|---|---|---|
| Center of mass energy (GeV) | 7.4 | 7.4 | 6.2 |
| Integrated luminosity ($10^{35}$ cm$^{-2}$) | 4.26 | 0.77 | 1.26 |
| Radiative correction (to lowest-order rate in spectrometers) | 0.93 | 0.93 | 0.93 |
| Number of events expected (point source) | 226.6 | 45.2 | 95.7 |
| Number of events observed (weighted sum) | 213.8 | 54.2 | 113.2 |
| Ratio of observed to expected events | $0.94 \pm 0.07$ | $1.19 \pm 0.19$ | $1.18 \pm 0.13$ |

and a tight correlation with the beam orbit, and are clearly due to the detection of muon pairs from SPEAR. No background due to cosmic-ray muons is observed for the range of time difference included in this plot. The qualitative appearance of the data at center-of-mass energies of 6.2 and 7.0 GeV is identical to that shown in Fig. 3. The estimated background due to collinear hadron-pair production, based on extrapolation of the measured cross sections of Barbiellini *et al.*[6] and Bernardini *et al.*,[7] is negligible at all three center-of-mass energies ($\leq 0.1$ event). The reaction $e^+e^- \to e^+e^-\mu^+\mu^-$ is expected to produce muon pairs satisfying the geometrical and range requirements of this experiment at a rate of less than 2% of that due to $e^+e^- \to \mu^+\mu^-$.[8] However, muons from this source have a rapidly falling energy spectrum and are subject both to large multiple scattering and magnetic deflections before reaching the muon-timing counters. The presence of any residual background from this source should be revealed in Fig. 4, which shows the distribution of the sum of the magnetic deflections observed in the two spectrometers for the $e^+e^- \to \mu^+\mu^-$ candidate events at a center-of-mass energy of 7.4 GeV. Two event peaks are observed, corresponding to the two possible charge states in each spectrometer, and for each the mean sum deflection is consistent with that expected (2.4 in.) due to muons with the full beam energy. Also, the width of each of these event peaks is consistent with that expected (1.0 in.) due to multiple scattering of muons with the full beam energy. No events can be associated with the reaction $e^+e^- \to e^+e^-\mu^+\mu^-$.

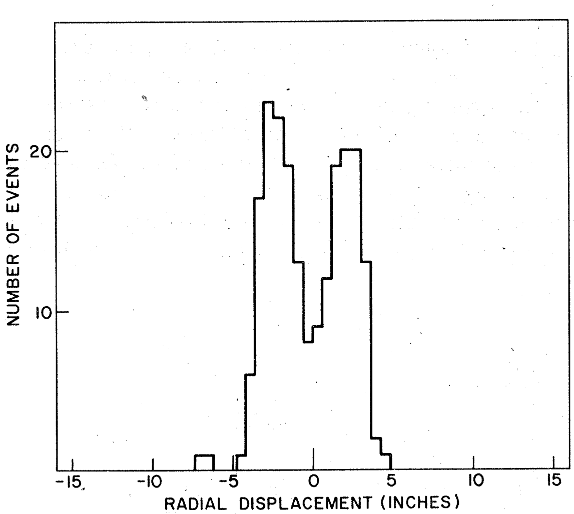


FIG. 4. The distribution of the sum of the radial deflections observed in the two toroidal magnets for 210 $e^+e^- \to \mu^+\mu^-$ candidate events at a center of-mass energy of 7.4 GeV. The field directions in the magnets are such that the direction of the magnetic deflection is the same in both spectrometers for a pair of oppositely charged particles.

In order to compare the number of $e^+e^- \to \mu^+\mu^-$ events observed in this experiment with QED it is necessary to take into account the longitudinal profile of the luminous region.[9] This is done by assigning a weight factor to each event, which depends only on the displacement of the event vertex from the center of the luminous region, and which corrects for the geometrical bias against the acceptance of events for which this displacement is nonzero. The weighted sum of the observed number of events is then compared to the expected number of events for a point luminous region. The weighted event sums, together with the numbers expected from QED, are shown in Table I. The radiative corrections, including a correction of 4.0% to the observed luminosities, are computed according to Berends *et al.*[10] The weight factor for each event is also computed according to Berends *et al.* The total systematic error assigned to the expected event numbers is ±2%.[11]

The conclusion to be drawn from Table I is that the rates we observe are in agreement with those expected from QED. In particular, at 7.4 GeV, when the majority of the data were accumulated and the timelike value of $q^2$ is 54.8 (GeV/$c$)$^2$, the validity of QED for the muon-pair-annihilation reaction is verified to a precision of ±7%. This re-

TABLE II. The lower limits (95% confidence level) on the cutoff parameters $\Lambda_+$ and $\Lambda_-$ set by this and an earlier experiment.

| | $\Lambda_+$ (GeV) | $\Lambda_-$ (GeV) |
|---|---|---|
| This experiment | 30.0 | 30.5 |
| Ref. 14 | 11.9 | 22.8 |

sult demonstrates the validity of QED, to this level of precision, at distances as small as $\sim 3\times 10^{-15}$ cm in the reaction $e^+e^- \to \mu^+\mu^-$. If, as usual, we anticipate that a possible breakdown of QED can be described by a propagator modification in the lowest-order Feynman diagram of the form

$$1/q^2 \to (1/q^2)[1 \pm q^2/(q^2 - \Lambda_\pm^2)]$$

(Refs. 12, 13), then our results can be used to place new lower limits (95% confidence level) on the cutoff parameters $\Lambda$ which, in this experiment, relate to the timelike photon propagator. These values, together with the limits set by an earlier experiment,[14] are given in Table II.

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