Volume 166B, number 4 PHYSICS LETTERS 23 January 1986

PRECISION TEST OF QED BY DIRECT COMPARISON OF $e^+e^- \to \gamma\gamma$ AND $e^+e^- \to e^+e^-$ AT 29 GeV

M. DERRICK, K.K. GAN, P. KOOIJMAN, J.S. LOOS, B. MUSGRAVE, L.E. PRICE,
J. SCHLERETH, K. SUGANO, J.M. WEISS [1], D.E. WOOD [2]

Argonne National Laboratory, Argonne, IL 60439, USA

D. BLOCKUS, B. BRABSON, S.W. GRAY [3], C. JUNG, H. NEAL, H. OGREN, D.R. RUST,
M. VALDATA-NAPPI [4]

Indiana University, Bloomington, IN 47405, USA

C. AKERLOF, G. BONVICINI, J. CHAPMAN, D. ERREDE, N. HARNEW [5], P. KESTEN [6],
D.I. MEYER, D. NITZ, A.A. SEIDL [2], R. THUN, T. TRINKO [2], M. WILLUTZKY

University of Michigan, Ann Arbor, MI 48109, USA

S. ABACHI, P. BARINGER, I. BELTRAMI [7], B.G. BYLSMA, R. DEBONTE, D. KOLTICK,
F.J. LOEFFLER, E.H. LOW, R.L. McILWAIN, D.H. MILLER, C.R. NG, L.K. RANGAN,
E.I. SHIBATA

Purdue University, West Lafayette, IN 47907, USA

and

B. CORK

Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA

Received 31 October 1985

The ratio of differential cross sections for the reactions $e^+e^- \to \gamma\gamma$ and $e^+e^- \to e^+e^-$ is measured at $\sqrt{s} = 29$ GeV in the central polar angle region, $|\cos\theta| < 0.55$, and compared to the same ratio calculated by QED to order α^3. The ratio of these ratios, integrated over this angular region, is $1.007 \pm 0.009 \pm 0.008$, demonstrating excellent agreement between theory and experiment. The 95% confidence limits on the QED cut-off parameters for the $\gamma\gamma$ final state are $\Lambda_+ > 59$ GeV and $\Lambda_- > 59$ GeV.

A number of experimental tests of quantum electrodynamics (QED) in high energy e^+e^- annihilations have been performed in the past few years. Aside from small electroweak (GSW) effects [1], no evidence suggesting a departure from QED at small distances has been reported. The reactions

$$e^+e^- \to \gamma\gamma \quad (\gamma\text{-pair production}), \qquad (1)$$

$$e^+e^- \to e^+e^- \quad (\text{Bhabha scattering}), \qquad (2)$$

---

[1] Present address: SRI International, Menlo Park, CA 94025, USA.

[2] Present address: Lockheed Missiles and Space Co., Sunnyvale, CA 94086, USA.

[3] Present address: Laboratory for Nuclear Studies, Cornell University, Ithaca, NY 14853, USA.

[4] Present address: INFN, I-56010 Pisa, Italy.

[5] Present address: CERN, CH-1211 Geneva 23, Switzerland.

[6] Present address: Brandeis University, Waltham, MA 02254, USA.

[7] Present address: ETH, CH-8093 Zurich, Switzerland.

0370-2693/86/$ 03.50 © Elsevier Science Publishers B.V.
(North-Holland Physics Publishing Division)

are well-suited for such tests, since electroweak effects are absent in the $\gamma\gamma$ reaction and small in Bhabha scattering at PEP and PETRA energies. In particular, the ratio of the differential cross sections of these reactions provides a powerful check on the expectations of QED.

This paper reports measurements of these reactions at a center-of-mass energy of 29 GeV in the central polar angle region ($|\cos\theta| < 0.55$). The data correspond to an integrated luminosity of 165 pb^{-1} accumulated in the high resolution spectrometer (HRS) at the PEP storage ring at the Stanford Linear Accelerator Center. Both the statistical precision and the control of systematic uncertainties are improved over previously reported work on these reactions [2–5].

The HRS detector [6] has uniform and high efficiency for reconstructing tracks and electromagnetic showers at large polar angles. The detecting elements used in the present analysis are the 15-layer cylindrical central drift chamber (21 cm to 103 cm in radius), the two-layer system of drift tubes (189 cm mean radius), and the barrel calorimeter. All of these devices are located within the solenoidal magnetic field of 1.62 T. The momentum resolution is of high quality ($\sigma_p/p^2 = 0.0015\ \mathrm{GeV}^{-1}$ for full-length tracks), which is helpful in understanding bremsstrahlung and other non-gaussian effects that affect measurements of electron momenta. The total thickness of the beam pipe, vertex chamber, and inner wall of the central drift chamber is only 0.017 radiation lengths (r.l.), so that external bremsstrahlung and photon conversions cause only minor tracking losses and infrequent ambiguities in event identification. The combination of the high momentum resolution and the thin front end allows a better control of systematic uncertainties than has been possible in other experiments.

The barrel calorimeter is essential for the analysis of these reactions. It consists of 40 identical modules, each covering a 9° wedge in azimuth (ϕ) and spanning the polar angle range, $|\cos\theta| < 0.6$. Each module has two independent Pb-scintillator sandwiches (3 r.l. and 8 r.l.), between which is a plane of 14 proportional-wire tubes equipped with current division readout for the measurement of shower position in both θ and ϕ. The angular resolutions for electromagnetic showers are $\sigma_\phi = 7$ mrad and $\sigma_\theta = 8$ mrad. The energy resolution is well represented by $(\sigma_E/E)^2 = (0.16)^2/E\,(\mathrm{GeV}) + (0.07)^2$. The barrel time-of-flight system, which has a timing resolution of $\sigma_t = 190$ psec for high energy showers, is useful for rejecting cosmic rays and other backgrounds. The time-of-flight information also provides an independent measurement of the shower location; this is particularly useful for photons that begin to shower in the 8 r.l. section beyond the proportional-wire plane.

Events from reactions (1) and (2) have been analyzed together using similar techniques in order to minimize systematic uncertainties in relative normalization. All candidate events satisfied just one hardware trigger demanding a total energy deposit of at least 4.8 GeV in the barrel calorimeter. After passing through track and shower reconstruction programs, candidate events were retained that satisfied all following criteria:

(a) four or fewer reconstructed tracks,

(b) $E > 3.0$ GeV for (at least) two showers,

(c) $|\cos\theta| < 0.6$ for (at least) two showers,

(d) acolinearity <0.25 rad between any pair of showers or between any two tracks having $p > 7.5$ GeV/c.

Care was taken at this stage to identify and eliminate the small fraction (<1%) of experimental runs that had significant detector failures, or that were inadvertently duplicated in the data processing.

An event from reaction (1) [reaction (2)] was included in the final sample if it satisfied all the following stricter "standard" selections:

(a′) zero tracks [two tracks of opposite charge having $p > 7.5$ GeV/c],

(b′) $E > 3.75$ GeV for at least two showers [matched to tracks],

(c′) $|\cos\theta| < 0.55$ for the showers [charged tracks],

(d′) acolinearity <0.20 rad for any pair of showers [charged tracks],

(e′) times-of-flight within ±2.5 ns of the expected arrival time.

A small fraction of legitimate events passed (a)–(d) but failed the standard selections because of reconstruction failures, external photon conversions, knock-on electrons, or other causes. In order to recover these events, all of the one-, three-, and four-track candidates and those zero- and two-track candidates that had multiple showers or a substandard reconstruction of a shower or track, some 6500 events in all, were examined in detail by a physicist.

The data samples are summarized in table 1. Most events satisfy the standard selections (93% of the 14 880 γ-pairs and 97% of the 84 423 Bhabha events), but the numbers of events recovered by the physicist scan are still significant. This method of handling problem events accounts for every candidate, and therefore is systematically more reliable than methods that estimate such losses by means of photon conversion probabilities and Monte Carlo simulation of detector performance. Corrections to the observed event totals and the associated estimates of the systematic uncertainties are also given in table 1. The individual systematic uncertainties are independent, and therefore are summed in quadrature to

Table 1
Observed event samples, corrections, and estimates of systematic uncertainties.

Tracks	Reaction	
	$e^+e^- \to \gamma\gamma$	$e^+e^- \to e^+e^-$
0	13833 [a]	–
	403 [b]	
	173 [c]	
1	33 [d,e]	682 [e,f]
2	424 [d]	81992 [a]
	13 [c,d]	629 [e,f]
3	–	247 [g]
		503 [h]
		146 [e,f,h]
4	–	183 [d,i]
		41 [g,h]
observed event total	14880	84423
shower leakage loss [j] (%)	5.9 ± 0.4	2.1 ± 0.2
unused or ambiguous [k] (%)	0.2 ± 0.3	0.0 ± 0.1
contaminations [l] (%)	<0.1	<0.1
event cuts [m] (%)	0.0 ± 0.3	0.0 ± 0.2
external bremsstrahlung [n]	–	0.0 ± 0.3
corrected event total	15850	86190
statistical uncertainty (%)	0.8	0.4
systematic uncertainty (%)	0.6	0.5

[a] Satisfies all standard selection criteria.

[b] Possible confusion in shower; event confirmed by scan.

[c] Identified by scan to be $\gamma\gamma\gamma$; satisfies $\gamma\gamma$ selections.

[d] External conversion of γ in beam pipe, chamber walls, or chamber gas.

[e] One track fails to reconstruct or is falsely reconstructed.

[f] Direction of missing track determined from matching shower.

[g] Track eliminated by scan as being a knock-on electron or from an asymmetric external γ conversion.

[h] Spurious track eliminated by scan.

[i] Identified by scan to be $e^+e^-\gamma$; satisfies Bhabha selections.

[j] At azimuthal structures between barrel modules; independent of polar angle.

[k] Events identified by scan but not used; uncertainty estimate includes ambiguities from $\gamma\gamma$ interactions or higher-order QED processes.

[l] Cosmic-ray showers, beam-gas collisions, hadronic annihilations, or $\tau^+\tau^-$ pairs.

[m] Determined from data by varying the fiducial, acolinearity, and momentum cuts.

[n] Hard external bremsstrahlung causes a loss of 2.7% of the Bhabha events (corrected in the Monte Carlo simulation of the experiment); the estimated systematic uncertainty is 0.3%.

yield overall systematic uncertainties of 0.6% and 0.5% for reactions (1) and (2), respectively.

A direct bin-by-bin comparison of the differential cross sections for the two reactions is shown in fig. 1a, where

$$F(\cos\theta) = N_{\gamma\gamma}(\cos\theta)/[N_{ee}(\cos\theta) + N_{ee}(-\cos\theta)]\,, \qquad (3)$$

and $N(\cos\theta)$ is the corrected number of observed events in any cos θ bin. The uncertainties shown are statistical. The curve in fig. 1a is the prediction of QED theory for $F(\cos\theta)$, including a small (~1%) electroweak correction to Bhabha scattering [‡1]. The QED calculations for both reactions have been done using the programs of Berends and Kleiss [9], which include all effects to order α^3. These programs use Monte Carlo techniques to simulate the events of reactions (1) and (2), including the radiative final states, $\gamma\gamma\gamma$ and $e^+e^-\gamma$. In order to compare the calculations to this experiment, the simulated events are first smeared according to the known experimental resolutions and are then subjected to the same selections that are imposed on the data.

The agreement between theory and experiment in fig. 1a is excellent over the whole central angular region ($\chi^2/n_D = 15.9/22$). For the entire sample, the result is:

$$\frac{\Sigma(\mathrm{expt.})}{\Sigma(\mathrm{QED})} = 1.007 \pm 0.009 \pm 0.008 \pm \delta(\alpha^3)\,, \qquad (4)$$

where Σ represents the integral of $F(\cos\theta)$ over $|\cos\theta| < 0.55$. The first uncertainty is statistical, the second is systematic, and the term $\delta(\alpha^3)$ represents the uncertainty in the ratio of the theoretical cross sections calculated with QED to order α^3. The value of $\delta(\alpha^3)$ is unknown, but is estimated to be in the range of 1% [10]. The overall experimental accuracy of this comparison is 1.2% if the statistical and systematic uncertainties are added in quadrature or 1.7% if they are added linearly.

The γ-pair reaction alone is compared to QED in fig. 1b, where the ratio of the observed-to-calculated differential cross sections is shown. The normalization corresponds to an integrated luminosity of 164.4 pb^{-1}, obtained from the Bhabha sample. The agreement between QED and this reaction is again excellent ($\chi^2/n_D = 14.6/21$). Limits on the violation of QED for this reaction are commonly parameterized in terms of cut-off parameters [11,12]:

$$(d\sigma(e^+e^- \to \gamma\gamma)/d\Omega)/(d\sigma/d\Omega)_{\mathrm{QED}}$$
$$= 1 \pm (s^2/2\Lambda_\pm^4)\sin^2\theta\,. \qquad (5)$$

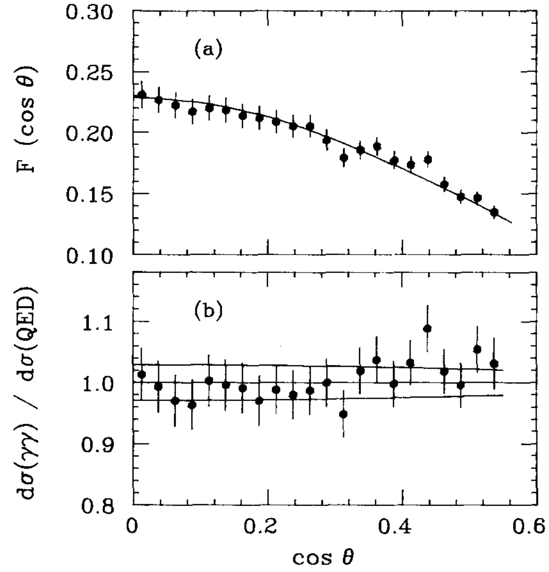

Fig. 1. (a) Direct comparison of the reactions $e^+e^- \to \gamma\gamma$ and $e^+e^- \to e^+e^-$ at a center-of-mass energy of 29 GeV. $F(\cos\theta)$ is the ratio of the γ-pair differential cross section to Bhabha differential cross section, where the latter is folded at $\cos\theta = 0$. The curve shows the expectation of QED to order α^3 together with a small (~1%) correction for electroweak effects. (b) Ratio of the observed-to-expected differential cross section for $e^+e^- \to \gamma\gamma$. The upper and lower curves, respectively, represent the limits (95% confidence level) for the QED cut-off parameters, $\Lambda_+ > 59$ GeV and $\Lambda_- > 59$ GeV.

The 95% confidence limits found from this experiment are $\Lambda_+ > 59$ GeV and $\Lambda_- > 59$ GeV, and the curves corresponding to these limits are shown in fig. 1b. In determining these limits, the integrated luminosity has been varied within the uncertainty of the Bhabha normalization. The value of Λ_+ may be interpreted [12] as a lower limit on the mass of a heavy electron that could be exchanged in reaction (1).

[‡1] The electroweak parameters used are $\sin^2\theta_W = 0.217$ and $M_Z = 93$ GeV/c^2 [7,8], but the correction is quite insensitive to these parameters.

In conclusion, the present experiment demonstrates that the predictions of α^3 QED are valid to within an accuracy of 2% or better. For comparison, previous PETRA experiments [2–5] have analyzed roughly half as many events as this experiment, and also have reported systematic uncertainties of 3% or greater arising from luminosity measurements or event identification inefficiencies. Therefore, the present results provide the most stringent test of QED yet reported in the PEP or PETRA energy range.

Work supported by the US Department of Energy under Contracts W-31-109-Eng-38, DE-AC02-76ER01112, DE-AC03-76SF00098, DE-AC02-76ER01428, and DE-AC02-84ER40125. We thank the technical staff at SLAC and the collaborating institutions for their efforts during this experiment, especially J. Nolen, M. Martin, E. Patterson and the PEP operators, and R. Watt and the cryogenics group.

References

[1] S.L. Glashow, Nucl. Phys. 22 (1961) 579;
A. Salam and J.C. Ward, Phys. Lett. 13 (1964) 168;
S. Weinberg, Phys. Rev. Lett. 19 (1967) 1264; Phys. Rev. D5 (1972) 1412.

[2] MARK J Collab., B. Adeva et al., Phys. Rev. Lett. 53 (1984) 134.

[3] TASSO Collab., M. Althoff et al., Z. Phys. C26 (1984) 337.

[4] JADE Collab., W. Bartel et al., Z. Phys. C19 (1983) 197.

[5] CELLO Collab., H. J. Behrend et al., Phys. Lett. 123B (1983) 127.

[6] HRS Collab., D. Bender et al., Phys. Rev. D30 (1984) 515.

[7] W.J. Marciano and S. Sirlin, Phys. Rev. D29 (1984) 945.

[8] UA1 Collab., G. Arnison et al., Phys. Lett. 147B (1984) 241;
UA2 Collab., M. Bagnaia et al., Phys. Lett. 129B (1983) 130.

[9] F.A. Berends and R. Kleiss, Nucl. Phys. B186 (1981) 22; Nucl. Phys. B228 (1983) 537.

[10] Y.S. Tsai, Report No. SLAC-PUB-3129 (1983), unpublished;
MAC Collab., E. Fernandez et al., Phys. Rev. D31 (1985) 1537.

[11] S.D. Drell, Ann. Phys. 4 (1985) 75.

[12] A. Litke, Ph.D. Thesis, Harvard University (1970), unpublished.