

## TEST OF QUANTUM ELECTRODYNAMICS AT PETRA

JADE Collaboration

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Differential cross sections for the reactions  $e^+e^- \rightarrow e^+e^-$  and  $e^+e^- \rightarrow \gamma\gamma$  are given for energies between 27.7 and 31.6 GeV. The results agree with the predictions of standard quantum electrodynamics and set lower limits to the usual cut-off parameters of up to 104 GeV. A limit on the Weinberg angle,  $\sin^2\theta_W < 0.63$ , is obtained at unprecedentedly high  $q^2$ .

We report here on a test of the theory of quantum electrodynamics (QED) through a study of the reactions  $e^+e^- \rightarrow e^+e^-$  (Bhabha scattering) and  $e^+e^- \rightarrow \gamma\gamma$  at center-of-mass energies between 27.7 and 31.6 GeV. At these energies only the process  $e^+e^- \rightarrow \gamma\gamma$  is ex-

pected to provide a clean test of QED. For a comparison of the Bhabha scattering data with theory hadronic vacuum polarization must be taken into account, and weak interaction effects are expected to become observable when sufficient statistical precision is achieved. It therefore becomes appropriate to enlarge the framework of the theoretical analysis of Bhabha scattering.

The experiment was carried out with the JADE detector at the  $e^+e^-$  colliding beam facility PETRA at DESY. A description of the JADE detector has ap-

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peared in a previous publication [1]. The essential part of the detector for this analysis is the array of lead-glass shower counters, which consists of 2712 blocks and covers the regions of polar scattering angle ( $\theta$ ):  $|\cos \theta| < 0.82$  (barrel) and  $0.89 < |\cos \theta| < 0.97$  (end caps). The fine granularity of the lead-glass counters allows an accurate measurement of the emission angles (typically  $\Delta\theta = \pm 0.6^\circ$  using the known interaction point) [2]. All counters were tested and calibrated with the test beam facility at DESY. The energy resolution of the individual counters was measured to be  $\Delta E/E = \pm 6\%/\sqrt{E(\text{GeV})}$  up to  $E = 6$  GeV. The overall energy resolution actually achieved for 15 GeV electron showers is  $\pm 3.8\%$ . The jet chamber and the beam pipe counters were used in this analysis only to separate  $e^+e^- \rightarrow \gamma\gamma$  from the Bhabha reaction. No attempt has been made to distinguish electrons from positrons in the Bhabha scattering events. The detector has full azimuthal symmetry around the beam axis, and this ensures that our results are not affected by any transverse polarization of the circulating beams so long as events are summed over all azimuthal angles.

The data evaluated here were taken at fixed energies of  $\sqrt{s} = 27.7, 30.0$  and  $31.6$  GeV, and over the range  $29.90$  to  $31.46$  GeV, which was scanned in steps of  $0.02$  GeV. All data were grouped into one of three energy bins with average  $\sqrt{s} = 27.7, 30.1$  and  $31.3$  GeV. Events from both of the reactions under study were taken with the so called "shower energy trigger", which required the detection of more than  $4$  GeV in the lead-glass in coincidence with the crossing of the beams. Candidate events for these reactions were selected by requiring at least two clusters of energy in the lead-glass, each having more than one third of the single beam energy. It was further required that the two lines joining the clusters to the center of the interaction region be parallel to within  $10^\circ$ . (The angle in space between these two lines will be referred to as the "acollinearity angle".) These criteria were sufficient to reduce the background (mostly cosmic ray events) to a low level ( $< 1\%$ ).

The  $\gamma\gamma$  events were then distinguished by requiring that at least one of the energy clusters not lie in the path of any track in the jet chamber or, in the case of tracks too near the beam axis to reach the chamber, in the scintillation counters surrounding the beam pipe. This selection was not fully efficient for the end cap events since accidental background signals occurred in

the beam pipe counters and occasionally made it appear that both energy clusters were associated with charged tracks. The probability of losing an end cap  $\gamma\gamma$  event in this way was found to be  $11 \pm 2\%$ . All events in the barrel region and the  $\gamma\gamma$  events in the endcaps were scanned by physicists, and the small surviving background was rejected. The selection of Bhabha scattering events in the end cap region was fully automatic, and scanning of a sample of approximately 2000 selected events revealed no background. The contamination of the Bhabha event sample by the reactions  $e^+e^- \rightarrow \tau^+\tau^-$  and  $e^+e^- \rightarrow e^+e^-e^+e^-$  was calculated and found to be less than  $0.1\%$ . The final sample then consists of 3672 and  $2.59 \times 10^4$   $e^+e^-$  events and 378 and 301  $\gamma\gamma$  events in the barrel and endcap region, respectively.

Fig. 1 shows the spectrum of measured energy divided by beam energy for the clusters in the lead glass array from Bhabha events in the range  $\sqrt{s} = 29.9$ – $31.4$  GeV and at  $|\cos \theta| < 0.7$ . A clear peak is observed near unity. Fig. 2 shows the acollinearity angle distribution, up to  $40^\circ$ , for events satisfying all the Bhabha selection criteria except the acollinearity cut. Here the data of all the energy regions are combined. The solid curve shows the predictions of QED up to order  $\alpha^3$  [3], folded with the angular resolution of the lead-glass counters.

Small corrections (typically  $< 5\%$ ) have been made to the data points for electronic defects. The data for

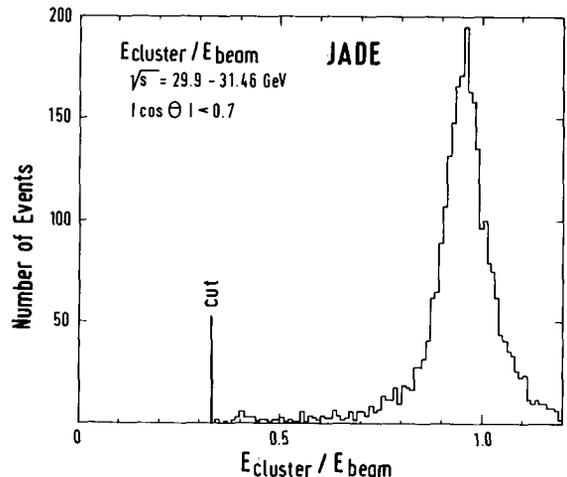


Fig. 1. Distribution of lead-glass cluster energy divided by beam energy for Bhabha events in the range  $29.9 \text{ GeV} \leq \sqrt{s} \leq 31.46 \text{ GeV}$ .

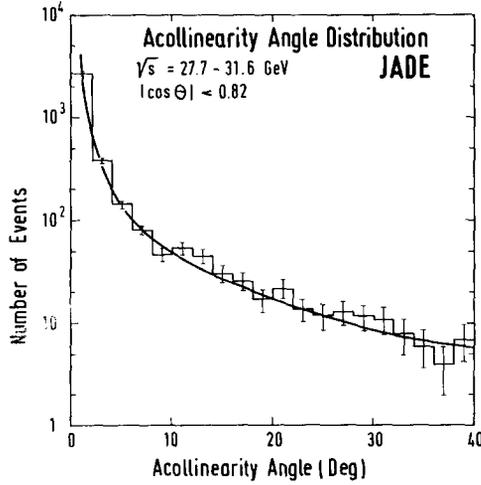


Fig. 2. Acollinearity distribution for Bhabha events. The data of all the energy regions are combined. The curve is the prediction of QED up to order  $\alpha^3$ .

$e^+e^- \rightarrow \gamma\gamma$  were further corrected for those  $e^+e^- \rightarrow \gamma\gamma$  events in which both photons had converted in the material between the jet chamber and the beam, resulting in the event being classified as  $e^+e^- \rightarrow e^+e^-$ . This correction amounted to 2% at  $90^\circ$  scattering angle, at which each photon encounters 0.18 radiation length, and 11% at the smallest scattering angle. The contamination of the Bhabha event sample by this background is negligible.

Absolute luminosities can be obtained from Bhabha scattering in the end cap lead-glass counters ( $0.91 < |\cos \theta| < 0.97$ ) provided standard QED is correct at small angles. The integrated luminosities so obtained are:  $196 \pm 9$ ,  $1144 \pm 39$ ,  $790 \pm 28 \text{ nb}^{-1}$  at  $\sqrt{s} = 27.7$ , 30.1 and 31.3 GeV, respectively, where the errors are systematic ( $2.5\% \sigma$ ) and statistical. The acceptance of the end caps was computed with the aid of detailed Monte Carlo simulations of the Bhabha scattering process, with radiative corrections, and of the propagation of the scattered particles through the material in and around the detector. Absolute luminosities were used only in comparing the data on  $e^+e^- \rightarrow \gamma\gamma$  with the predictions of QED and hypothetical modifications thereof. In the study of Bhabha scattering the luminosity was adjusted appropriately for each trial modification of the standard QED scattering cross section, so that the comparison between prediction and measurement is based on the shape of the scattering angle distribution and not on any absolute normalization.

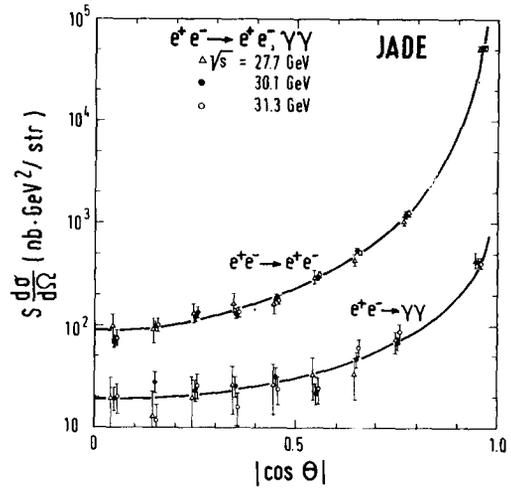


Fig. 3. Angular distributions for the reactions  $e^+e^- \rightarrow e^+e^-$  and  $e^+e^- \rightarrow \gamma\gamma$  at  $\sqrt{s} = 27.7, 30.1$  and  $31.3$  GeV. The curves are the predictions of QED.

Fig. 3 shows the measured scattering angle distributions for the two reactions studied. The data points in the region  $0.70 < |\cos \theta| < 0.82$ , near the limits of the barrel's acceptance, have been corrected for events lost due to shower energy leakage from the lead-glass. The systematic error on the acceptance in this region has been estimated at  $\pm 5\%$  and was included in the error bars on fig. 3. The curves in fig. 3 were calculated from QED. Radiative corrections [4] and, in the case of Bhabha scattering, a correction for hadronic vacuum polarization [5] have been applied.

There is an excellent agreement between the data and the QED predictions. In order to express the result in terms of a cut-off parameter  $\Lambda$ , we introduce a hypothetical modification [6] of the photon propagator  $1/q^2$  by multiplying it with a form factor

$$F(q^2) = 1 \pm q^2/(q^2 - \Lambda_{\pm}^2),$$

where  $q^2$  is the invariant mass squared of the virtual photon. Then the differential cross section is given by:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} \left[ \frac{10 + 4x + 2x^2}{(1-x)^2} F^2(q^2) - \frac{2(1+x)^2}{1-x} F(q^2)F(s) + (1+x^2)F^2(s) \right],$$

where  $x = \cos \theta$  and  $q^2 = -s(1-x)/2$ .

For the reaction  $e^+e^- \rightarrow \gamma\gamma$  we use [7]

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{s} \frac{1+x^2}{1-x^2} \left[ 1 \pm \frac{s^2}{2\Lambda_{\pm}^4} (1-x^2) \right].$$

Here the cut-off parameter  $\Lambda_+$  can be regarded as the ratio of the mass to the coupling constant of a possible heavy electron which mediates the reaction. A limit on the parameter  $\Lambda_-$ , though theoretically rather unmotivated, is presented for completeness.

In the case of the Bhabha scattering reaction a single, overall  $\chi^2$  fit of the theoretical cross section with modified photon propagator to the scattering angle distribution of fig. 3 was made for each trial value of  $\Lambda_+$  or  $\Lambda_-$ . All points within the angular range  $|\cos \theta| < 0.82$  and from all three energies entered each fit simultaneously. The  $\chi^2$  values were used to set lower limits to  $\Lambda_+$  and  $\Lambda_-$ . The given angular range excludes the end cap region, from which the luminosity normalization was obtained, although as noted above the luminosities were adjusted for changes in the parameters  $\Lambda$ . The changes in luminosity corresponding to the lower limits on  $\Lambda_+$  and  $\Lambda_-$  are approximately 1%. Specifically, the  $\chi^2$  function can be written as:

$$\chi^2(\Lambda) = \sum_{E=1}^3 \left\{ \sum_{B=1}^8 \frac{[n_{EB} - (1+a_E)(1+b)L_E(\Lambda)\sigma_{EB}(\Lambda)]^2}{n_{EB}} + \left( \frac{a_E}{\Delta L_E} \right)^2 \right\} + \left( \frac{b}{DL} \right)^2.$$

The index  $E$  runs over the three  $\sqrt{s}$  ranges while  $B$  labels the eight scattering angle bins in the barrel region into which the data are grouped. The  $n_{EB}$  are the numbers of events for each  $\sqrt{s}$  and angle bin. The  $L_E(\Lambda)$  are the integrated luminosities for each of the  $\sqrt{s}$  and, in the case of Bhabha scattering, depend weakly upon the parameter  $\Lambda$ . The  $a_E$  are the fractional statistical fluctuations of the measured  $L_E$  from the true values, while the single variable  $b$  is the analogous systematic error, assumed to be independent of  $\sqrt{s}$ . The  $\Delta L_E$  and the single  $DL$  are the corresponding statistical and systematic uncertainties, respectively. Finally the  $\sigma_{EB}(\Lambda)$  are the cross sections for observing an event within the labelled angled bin and at the labelled  $\sqrt{s}$ , calculated from QED as modified for each value of  $\Lambda$  including radiative corrections.

For each trial value of  $\Lambda$ ,  $\chi^2$  is minimized by vary-

ing  $b$  and the three  $a_E$ . The 95% confidence level lower limits on  $\Lambda_+$  and  $\Lambda_-$  are those values at which  $\chi^2$  is 4 units [8] greater than the minimum value for any  $\Lambda$ .

For the reaction  $e^+e^- \rightarrow \gamma\gamma$  all the points of fig. 3 within the angular range  $|\cos \theta| < 0.97$  were used in  $\chi^2$  fits analogous to those made to the Bhabha scattering data, and lower limits were obtained to the  $\Lambda$ 's. The luminosities as measured with Bhabha scattering in the end cap region were treated as fixed constants.

Table 1 lists the lower limits on the parameters  $\Lambda$  at the 95% CL together with the limits set by earlier experiments.

Since Bhabha scattering at these energies starts to be sensitive to the effects of the weak interaction, the measured differential cross sections for this reaction were also fitted to the theoretical predictions incorporating the standard Weinberg-Salam model [9].

The differential cross section is given by:

$$\begin{aligned} \frac{d\sigma}{d\Omega} = & \frac{\alpha^2}{4s} \left( \frac{3+x^2}{1-x} \right)^2 \\ & + 2 \frac{3+x^2}{(1-x)^2} [(3+x)Q - x(1-x)R]v^2 \\ & - \frac{2}{1-x} [(7+4x+x^2)Q + (1+3x^2)R] \\ & + \frac{1}{2} \left[ \frac{16}{(1-x)^2} Q^2 + (1-x)^2 R^2 \right] (v^2 - 1)^2 \\ & + \frac{1}{2} (1+x)^2 \left( \frac{2}{1-x} Q - R \right)^2 (v^4 + 6v^2 + 1) \end{aligned}$$

Table 1  
Lower limits on the cut-off parameter (in GeV) (95% confidence level).

Experiment	$e^+e^- \rightarrow e^+e^-$		$e^+e^- \rightarrow \gamma\gamma$	
	$\Lambda_+$	$\Lambda_-$	$\Lambda_+$	$\Lambda_-$
this experiment	104	87	45	38
ref. [10]	38.0	33.8		
ref. [11]	95	74		
ref. [12]	230	79		
ref. [13] a)			10.7	9.0

a) These authors use a definition of  $\Lambda$  which differs slightly from ours. Their data are however all for scattering angles very near  $90^\circ$ , at which angle the two definitions coincide.

where

$$Q = 4.49 \times 10^{-5} M_Z^2 q^2 / (q^2 - M_Z^2),$$

$$R = 4.49 \times 10^{-5} M_Z^2 s / (s - M_Z^2),$$

$$v = 4 \sin^2 \theta_W - 1, \quad M_Z = 74.6 / \sin(2\theta_W) \text{ (GeV)}.$$

This fit provides a limit on the Weinberg angle of  $\sin^2 \theta_W < 0.63$  (95% CL),

where it has here been assumed that there are no modifications of the standard QED photon propagator. It should be noted that this is the first test of the model at such high  $q^2$  (ranging up to 1000 GeV<sup>2</sup>).

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### References

- [1] JADE Collab., W. Bartel et al., Phys. Lett. 88B (1979) 171.
- [2] D.P. Barber et al., Nucl. Instrum. Methods 145 (1977) 453;  
R. Carrington et al., Nucl. Instrum. Methods 163 (1979) 203.
- [3] K. Sauerberg, Ph.D. Thesis, DESY Internal Report F22-79/01 (1979).
- [4] F.A. Berends et al., Nucl. Phys. B61 (1973) 414; B68 (1974) 541.
- [5] F.A. Berends and G.J. Komen, Phys. Lett. 63B (1976) 432.
- [6] S.D. Drell, Ann. Phys. 4 (1958) 75;  
T.D. Lee and G.C. Wick, Nucl. Phys. B9 (1969) 209.
- [7] A. Litke, Harvard Univ., Ph.D. Thesis (1970), unpublished.
- [8] See, for example, D.J. Hudson, CERN 64-18 (1964).
- [9] R. Budny, Phys. Lett. 55B (1975) 227.
- [10] L.H. O'Neill et al., Phys. Rev. Lett. 37 (1976) 395.
- [11] D. Barber et al., Phys. Rev. Lett. 43 (1979) 1915.
- [12] PLUTO Collab., DESY 80/01, to be published.
- [13] E. Hilger et al., Phys. Rev. D15 (1977) 1809.