A STUDY OF THE THREE- AND FOUR-PHOTON FINAL STATES PRODUCED IN e^+e^- ANNIHILATION AT $35 \leqslant \sqrt{s} \leqslant 46.8$ GeV

CELLO Collaboration

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The reactions $e^+e^- \to \gamma\gamma\gamma$ and $e^+e^- \to \gamma\gamma\gamma\gamma$ have been studied at center-of-mass energies between 35 and 46.8 GeV with an integrated luninosity of about 130 pb^{-1} accumulated with the CELLO detector at PETRA. The measurements are compared to QED calculations up to third and fourth orders of perturbation theory. Excellent agreement is observed.

1. Introduction

In this paper we present tests of quantum electro dynamics (QED) in e^+e^- annihilation into three- and four-photon final states. Since there is no weak interaction contribution to the lowest order of perturbation theory (α^3 for $e^+e^- \to \gamma\gamma\gamma$ and α^4 for $e^+e^- \to \gamma\gamma\gamma\gamma$, where α is the fine structure constant), e^+e^- annihilation into photons provides a clean test of QED.

The data were recorded by the CELLO detector operating at the PETRA e^+e^- storage ring, at energies in the range 35–46.8 GeV. The integrated luminosity of 130 pb^{-1} has allowed us:

(i) to perform precise measurements of e^+e^- annihilation into three energetic photons,

(ii) to observe 19 events with e^+e^- annihilation into four energetic photons. In this way we present for the first time data distributions for this channel, and compare them with the theoretical ones. The latter were obtained using a specially written Monte Carlo generator.

The CELLO detector is particularly well suited to investigate pure photon final states, due to its almost hermetic calorimetry covering more than 99% of the solid angle. After a short description of this calorimetry and of its performance, we present the event selection, the analysis and the results for the two processes mentioned above.

2. Detector description

A detailed description of the CELLO detector can be found in ref. [1]. Here we recall only the features essential for the study of purely electromagnetic neutral final states.

CELLO features hermetic calorimetry down to a polar angle of 50 mrad with respect to the beam axis. The main component is a 20 radiation length lead–liquid-argon calorimeter, with fine lateral and longitudinal segmentation and sixfold sampling in depth. The 16 modules of the "barrel" part, located in a single cryostat, cover the polar angle domain $|\cos\theta| < 0.86$ while the 4 "end-cap" modules span the range $0.92 < |\cos\theta| < 0.99$. This calorimeter provides an energy resolution parametrized as $\Delta E \sim 5\% E + 10\% \sqrt{E}$, E in GeV, and an angular resolution of ~ 5 mrad, in both azimuth and polar angle.

The calorimeter gap at $0.86 < |\cos\theta| < 0.92$ is closed by a lead scintillator sandwich, the so-called "hole tagger", with only rough energy and angular resolutions, but good vetoing capability.

The small angle tagger – a lead-glass counter covering the polar angle domain from 120 mrad down to 50 mrad – is used in this analysis only to check the integrated luminosity measurement whose precise value has been deduced from the number of $e^+e^- \to \gamma\gamma$ events observed in the central calorimeter. Table 1

Table 1
Energies and integrated luminosities of the data samples used in the analyses reported here.

$\sqrt{s}$(GeV)	$\mathscr{L}$(pb^{-1})
35.0	81.0
38.3	8.9
38.7–43.3	4.9
43.5	1.4
43.6	17.0
44.2	9.2
43.4–45.2	3.8
45.3–46.8	3.5
46.3	1.0

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summarizes the luminosities used for this study together with the corresponding beam energies.

The following trigger conditions were relevant for the study of pure photon final states: an energy deposition of at least 2 GeV in each of two barrel modules separated by at least 45° in aximuth, or an energy deposition of at least 3 GeV in one of the barrel modules.

The trigger efficiency is close to 100% for e^+e^- annihilation into three or four energetic photons fulfilling the selection criteria described below. This high efficiency is essentially due to the presence of at least one photon with an energy above $E_b/2(\sim 9$ GeV), where E_b is the beam energy, and at least photons with an energy above $E_b/3(\sim 6$ GeV) in the worst case.

3. The reaction $e^+e^- \to \gamma\gamma\gamma$.

To select purely neutral final states, we first performed a preselection using the following criteria:
- no reconstructed charged particle tracks,
- at least two showers in the barrel calorimeter with an energy deposition above 800 MeV each,
- not more than four showers with an energy deposition above 800 MeV each,
- at least two showers with an energy deposition above $E_b/4$ each.

Three-photon final states were selected as having exactly three showers with an energy above 800 MeV if detected in the barrel modules or 2 GeV if in the end-cap modules, the angular separation of each photon pair having to exceed 10°.

In order to reduce the cosmic background, it was also required that the total visible energy be above and the total momentum be below E_b.

Finally the radiative Bhabha background (with both electron tracks unreconstructed) was drastically reduced by requiring an acoplanarity of the two most energetic showers above 3°. For this three-photon process, we did not include the hole tagger information in the selection criteria.

Using the data sample shown in table 1, 889 candidates passed these cuts and were fitted to the $e^+e^- \to \gamma\gamma\gamma(\gamma)$ hypothesis – (γ) being emitted along the beam axis – with the measured energies and angles of the three detected photons as input.
667 events satisfied a four-constraint or three-constraint fit with a confidence level above 1%. A few energy dependent cuts were applied to this sample in order to take into account the large range of $\sqrt{s}$:
- the smallest photon energy had to be above $0.1E_b$,
- the energy of the undetected photon in the beam pipe had to be less than $0.2E_b$.

The remaining 522 events were inspected visually. Residual background events due to cosmic showers or with unreconstructed charged particle tracks were rejected. The features of these background events are quite easily recognized: extra showers and/or showers with a "wrong" longitudinal development in the liquid-argon–lead stacks as far as the cosmic ray events are concerned, strings of hits in the central tracking device in other cases. As a consequence, the error introduced by this rejection is negligible with respect to the statistical uncertainty which corresponds to the size of the final sample of events.

Finally we are left with 429 three-photon events, to be compared with an expectation of 441 ± 13, obtained using the $e^+e^- \to \gamma\gamma\gamma$ generator of Berends and Kleiss [2] modified to allow for the emission of an extra photon along the beam line. The error on the number of expected events reflects the uncertainty in the luminosity measurement[#1]. The detector response simulation takes into account the acceptance and the resolutions.

The theoretical differential cross section increases rapidly for events having at least one photon with a small polar angle and/or with a low energy. Therefore, photon polar angles and energies are adequate variables to test the dynamics of the process. The distributions of these quanities are shown in fig. 1, together with the QED expectation normalized to the observed number of events. Fig. 2 shows the Dalitz diagram of the three-photon pair squared invariant masses, in which three regions have been defined:

$W^2_{(3)}/s > 0.75$ Region I ,

$W^2_{(1)}/s > 0.4$ Region III ,

$W^2_{(3)}/s < 0.75$ and $W^2_{(1)}/s < 0.4$ Region II ,

where $W_{(1)}$, $W_{(2)}$ and $W_{(3)}$ are the $\gamma\gamma$ invariant

[#1] The virtual radiative corrections have not been calculated for the processes investigated in this paper. Therefore, their contribution has not been taken into account in the estimations of the expected number of events, nor in the corresponding error.

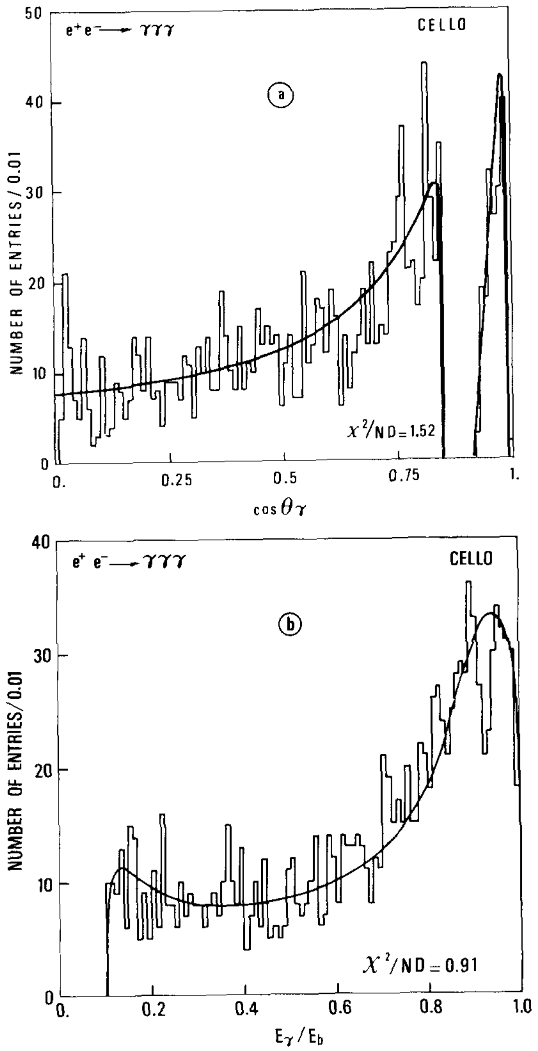

Fig. 1. Photon polar angle (a) and energy (b) distributions in the reaction $e^+e^- \to \gamma\gamma\gamma$ (3 entries per event). The curve represent the QED expectation. At least two photons out of three have to be in the barrel calorimeter acceptance ($|\cos\theta| \leqslant 0.86$).

masses in increasing order. Table 2 shows the comparison of the numbers of expected and observed events in each of these three regions.

All the data distributions and numbers of events are in excellent agreement with the α^3 QED expectation. Similar results have previously been reported [3,4].

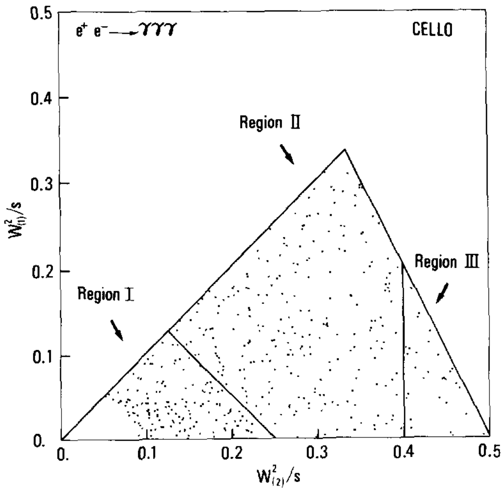

Fig. 2. Dalitz diagram for the reaction $e^+e^- \to \gamma\gamma\gamma$.

Table 2
Comparison of the numbers of expected and observed events in the three regions of the Dalitz diagram shown in fig. 2.

Region	Data	QED
I	137	154
II	260	250
III	32	37
Total	429	441

4. The reaction $e^+e^- \to \gamma\gamma\gamma\gamma$.

Following the preselection described above, four-photon final states were selected as having exactly four showers, at least three being in the barrel calorimeter with an energy above 800 MeV. A fourth shower had to have an energy above 800 MeV in the barrel calorimeter or in the hole tagger scintillators, above 2 GeV in the end-cap calorimeter. Angular separation, total shower energy and total momentum cuts were the same as above.

The 200 selected candidates were fitted to the $e^+e^- \to \gamma\gamma\gamma\gamma(\gamma)$ hypothesis. Among them 71 events statisfied a four- or three-constraint fit with a confidence level above 1%. Energy dependent cuts were applied to this sample also:
– the smallest photon energy had to be above $0.05E_b$, $0.05E_b$ or $0.1E_b$ in the barrel, hole tagger or end-cap respectively,

– the energy of the undetected photon in the beam pipe had to be less than $0.2E_b$.

The remaining 53 events were scanned. 34 background events were found which were due to cosmic showers or double radiative Bhabha scatters with two unreconstructed tracks. Here again this background rejection could be performed without any ambiguity. The number of genuine $e^+e^- \to \gamma\gamma\gamma\gamma$ events is 19. All of them satisfy a four-constraint fit with a confidence level above 5%.

In order to compare this number to the α^4 QED prediction, a Monte Carlo generator was developed for the four-energetic-photon final states [5], using the matrix element given in ref. [6]. This generator has been compared with calculations carried out by Kleiss and Stirling [7].

The simulation of the detector response and the analysis chain lead to a predicted observable cross section of 0.16 pb at $\sqrt{s}=35$ GeV. The expected number of events is 18.1 ± 0.6, in excellent agree-

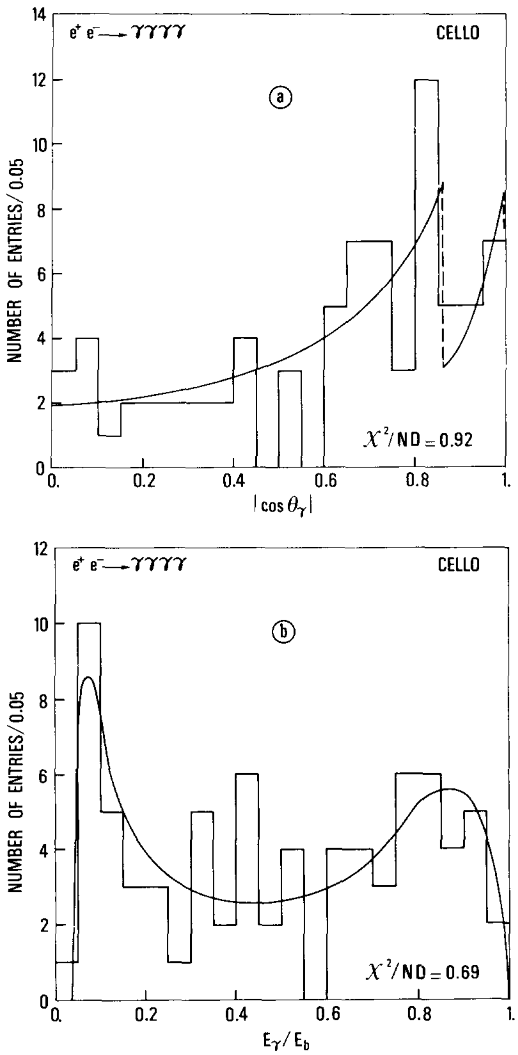

Fig. 3. Photon polar angle (a) and energy (b) distributions in the reaction $e^+e^- \to \gamma\gamma\gamma\gamma$ (4 entries per event). The curves represent the QED expectation. At least three photons out of four have to be in the barrel calorimeter acceptance ($|\cos\theta| \leqslant 0.86$).

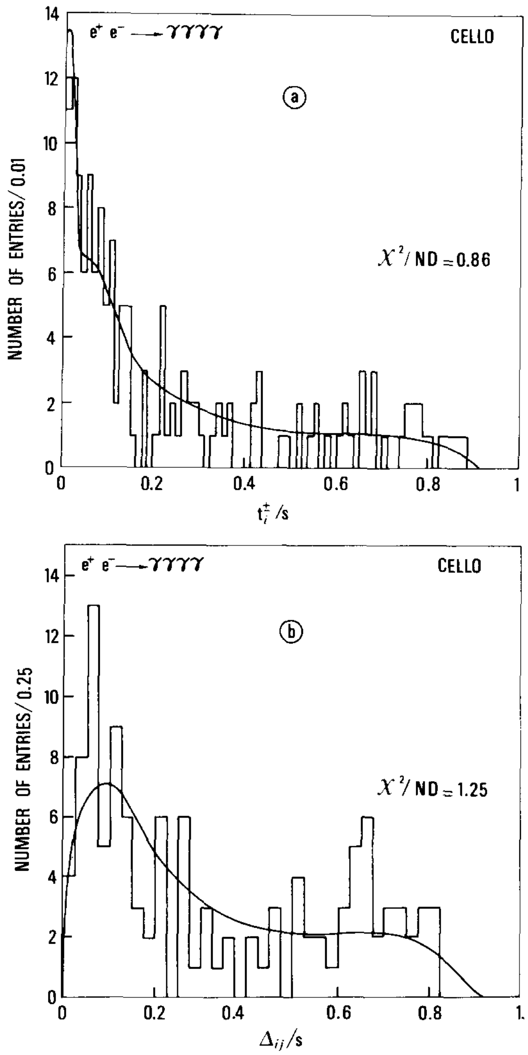

Fig. 4. Distribution of the moment transfers of the type $t_i^{\pm}/s = (p_{\pm} - k_i)^2/s$ (a) and $\Delta_{ij}/s = (p_- - k_i - k_j)^2/s$ (b) for the reaction $e^+e^- \to \gamma\gamma\gamma\gamma$ (8 and 6 entries per event). The curves represent the QED expectation.

ment with the 19 observed events. Here also, the error reflects the uncertainty in the luminosity measurement. Among these 19 events, 5 had the four photons in the barrel (6.1 expected), 3 had a photon in the hole tagger (4.0 expected) and 11 had a photon in the end-cap (8.0 expected).

The predictions of QED were checked in more detail by examining those kinematic variables which are the most significant with respect to the dynamics of the process. As before, the chosen quantities are the polar angles and the energies of the photons shown in fig. 3. In addition, fig. 4 shows the distributions of the squared momentum transfers:

$$t_i^{\mp} = (p_{\pm} - k_i)^2 ,$$

$$\Delta_{ij} = (p_- - k_i - k_j)^2 ,$$

where $p_{\pm}$ are the $e^{\pm}$ four momenta and $k_{i,j}$ the γ four-momenta ($i,j = 1,2,3,4$). Finally, fig. 5 shows the distributions of the $\gamma\gamma$ invariant masses and of the smallest $\gamma\gamma$ invariant mass per event. Again, very good agreement with the α^4 QED expectation is observed.

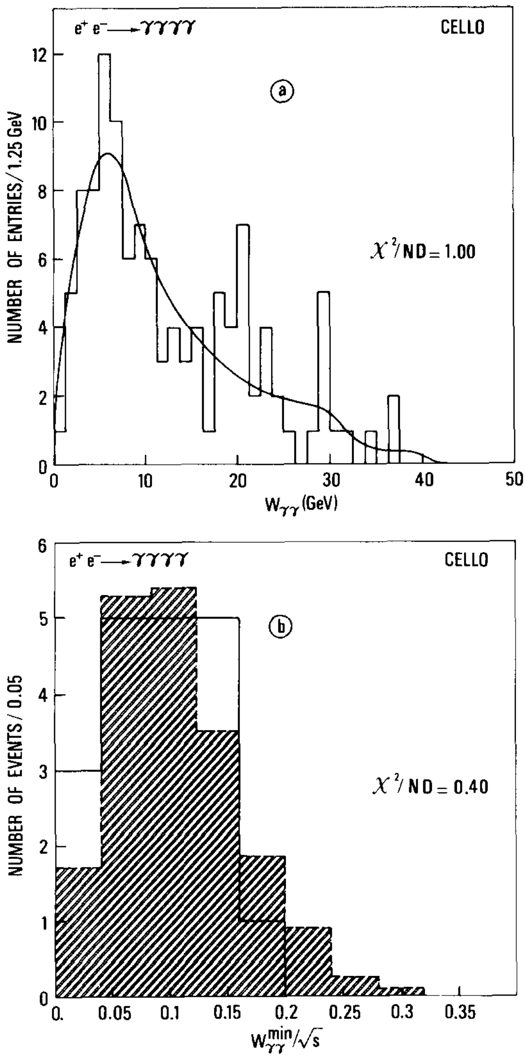

Fig. 5. Distributions of the six-photon pair invariant masses in GeV (a) and of the smallest invariant mass normalized to beam energy (b) for the reaction $e^+e^- \to \gamma\gamma\gamma\gamma$. The curve (a) and the hatched histogram (b) represent the QED expectations.

5. Conclusion

In none of the distributions relevant to the electron positron annihilation into three and four photons at PETRA energies have we observed any deviation from the QED predictions, calculated up to order α^4. 19 events with four photons in the final states have been observed, in good agreement with the theoretical expectation. Previously, only two such events had been reported [3]. Therefore the distributions presented in this letter provide the first detailed analysis of this fourth-order QED process ($e^+e^- \to \gamma\gamma\gamma\gamma$) observed in a high momentum transfer regime.

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