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A Study of the Reaction $e^+e^- \to \gamma\gamma$ at LEP

The OPAL Collaboration

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Abstract

The pure QED reaction $e^+e^- \to \gamma\gamma$ has been studied at centre of mass energies around the mass of the Z^0 boson using data recorded by the OPAL detector at LEP. The results are in good agreement with the QED prediction. Lower limits on the cutoff parameters of the modified electron propagator are found to be $\Lambda_+ > 82$ GeV and $\Lambda_- > 89$ GeV. The lower limit on the mass of an excited electron is 82 GeV assuming the coupling constant $\lambda = 1$. Upper limits on the branching ratios of $Z^0 \to \gamma\gamma$, $Z^0 \to \pi^0\gamma$ and $Z^0 \to \eta\gamma$ are set at 3.7×10^{-4}, 3.9×10^{-4} and 5.8×10^{-4} respectively. Two events from the reaction $e^+e^- \to \gamma\gamma\gamma$ have been observed, consistent with the QED prediction. An upper limit on the branching ratio of $Z^0 \to \gamma\gamma\gamma$ is set at 2.8×10^{-4}. All the limits are given at 95% confidence level.

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Quantum electrodynamics (QED) has been tested repeatedly in e^+e^- collisions through the production of lepton pairs and photon pairs. With the data from each new high energy e^+e^- collider the validity of QED has been verified in a new energy region. At centre of mass energies near the Z^0 mass lepton pair production is dominated by the weak interaction and hence is not adequate for tests of QED. In contrast, the reaction $e^+e^- \rightarrow \gamma\gamma$, which proceeds via the exchange of a virtual electron in the t-channel, still provides a clean test of QED in this energy region. The Z^0 has spin 1 and so the decay $Z^0 \rightarrow \gamma\gamma$ is strictly forbidden by Yang's theorem [1], and the effect of the Z^0 boson on radiative corrections to $e^+e^- \rightarrow \gamma\gamma$ is negligibly small. At LEP the centre of mass energy is approximately 1.5 to 3 times larger than that of previous measurements at TRISTAN, PETRA and PEP [2]. This can lead to more stringent limits on possible deviations from QED, even though the cross section of the reaction $e^+e^- \rightarrow \gamma\gamma$ is relatively small.

Observation of any significant deviation from the QED expectation near the Z^0 mass could be due to non-standard properties of the Z^0 boson. For example, the decay $Z^0 \rightarrow \pi^0\gamma$ has a similar experimental signature to $e^+e^- \rightarrow \gamma\gamma$ and can contribute to the measured cross section. Within the standard model the branching ratio of $Z^0 \rightarrow \pi^0\gamma$ has been calculated to be extremely small ($\sim 10^{-11}$) [3], but it has recently been suggested that it could be much larger ($\sim 10^{-3} - 10^{-5}$) [4]. The study of $\gamma\gamma\gamma$ final states not only checks the validity of radiative corrections but also provides a way to search for the Z^0-γ-γ-γ coupling which is predicted by some composite models [5].

The data were recorded with the OPAL detector [6] at LEP during a scan of the Z^0 resonance, at centre of mass energies ($\sqrt{s}$) between 88.28 and 95.04 GeV.

The components of the OPAL detector relevant to this analysis are described below. The trajectories and momenta of charged particles are measured by a central tracking detector in a uniform magnetic field of 0.435 T. It includes a precision vertex chamber, a large volume jet chamber which gives precise tracking information in the plane perpendicular to the beam direction and z-chambers for tracking in the plane parallel to the beam direction. The main tracking is done with the jet chamber, a drift chamber approximately four metres long and two metres in radius. It provides up to 159 measured space points along a track and covers the polar angular range of $|\cos\theta| < 0.97$. The barrel part of the electromagnetic calorimeter consists of 9440 lead glass blocks of 24.6 radiation lengths thickness pointing towards the interaction region. The barrel part covers the region $|\cos\theta| < 0.82$. The blocks are slightly tilted from a perfect pointing geometry to prevent photons from escaping through interblock gaps. The two endcaps of the electromagnetic calorimeter consist of 2264 lead glass blocks of 20 radiation lengths thickness, covering the polar angular range of $0.81 < |\cos\theta| < 0.98$. The forward detector, used for the luminosity measurement, is composed of two identical elements placed around the beam pipe at either end of the central detector, each consisting of a lead-scintillator calorimeter and proportional tube chambers. They cover the polar angles between 40 and 150 mrad and 2π in azimuthal angle. The systematic error in the determination of the integrated luminosity is estimated to be 2.2% [7].

For this analysis, the electromagnetic calorimeter, jet chamber and forward detector were all required to be operating at high efficiency. After these quality cuts, the remaining data correspond to an integrated luminosity of 684 nb^{-1}. The effective average centre of mass energy, calculated from the luminosity weighted mean value of $1/s$, is 91.16 GeV.

The triggers for $e^+e^- \rightarrow \gamma\gamma$ events are based on the electromagnetic calorimeter. The calorimeter trigger required an energy sum of at least 6 GeV in the barrel part or 10 GeV in one endcap. The trigger inefficiency for $e^+e^- \rightarrow \gamma\gamma$ events has been studied using $e^+e^- \rightarrow e^+e^-$ events, which had independent triggers, and was found to be negligible over the polar angular range of $|\cos\theta| < 0.95$.

The selection criteria for $e^+e^- \rightarrow \gamma\gamma$ events are:

i) The number of electromagnetic clusters with energies more than 0.2 GeV is required to be less than 9. This removes most of the multihadron events.

ii) At least two energetic electromagnetic clusters are required, each with an energy larger than 20% of the beam energy and $|\cos\theta| < 0.95$. From the events finally selected all but 5 clusters had energy above 90% of the beam energy, the lowest energy cluster having 44%. Some clusters well below the beam energy are expected due mainly to material in front of the calorimeter.

iii) The acollinearity angle of the two energetic clusters is required to be less than 5°.

iv) At least one of the two energetic clusters should be isolated from any charged track by more than 45° in azimuth. This allows one photon conversion in the $e^+e^- \to \gamma\gamma$ events and rejects most of the $e^+e^- \to e^+e^-$ events.

A total of 24 events satisfied these criteria. They were all visually scanned to eliminate most of the remaining background events. Three events were rejected at this stage : two are (a) $e^+e^- \to e^+e^-$ events with $|\cos\theta|$ close to 0.95, where the track reconstruction efficiency is reduced, and one is (b) $e^+e^- \to e^+e^-\gamma$, in which an electron and a photon are back-to-back and satisfy the selection criteria and the electron-positron pair is well separated. The number of events finally selected as $e^+e^- \to \gamma\gamma$ is 21. The numbers of selected events and the integrated luminosities are listed in table 1 for different centre of mass energies. The numbers of events seen in the barrel region ($|\cos\theta| < 0.8$) are also listed in table 1.

The remaining background from the process $e^+e^- \to e^+e^-(\gamma)$ has been estimated using Monte Carlo simulations. We generated 4900 $e^+e^- \to e^+e^-(\gamma)$ events within the range $|\cos\theta| < 0.95$, corresponding to 2.5 times the luminosity of the real data sample, using the BABAMC Monte Carlo program [8]. The events were processed by a program which simulates the response of the OPAL detector [9], and the same selection criteria, including the visual inspection, were applied to the simulated events as were applied to the real data. The numbers of Monte Carlo events rejected by the visual inspection were 2.8 and 1.6 events (normalised to the luminosity of the real data) for the backgrounds (a) and (b) respectively, which are consistent with the real data. The $e^+e^- \to e^+e^-\gamma$ events in which the electron and the positron are very close to each other and opposite to a high energy photon fake the reaction $e^+e^- \to \gamma\gamma$ with one photon conversion. Only one out of the 4900 generated events was of this type and hence the 68% confidence level upper limit on the number of such events in the data is 0.9. The $e^+e^- \to e^+e^-\gamma$ process in which one of the electrons scatters at small angles and escapes detection cannot be simulated by the BABAMC Monte Carlo program. Therefore this process was simulated using the TEEGG Monte Carlo program [10] and the contribution was found to be 0.2 events. Other backgrounds are negligibly small. Since the proportion of background events, 5.4% at most, is small compared to the statistical error on the measurement, this is included as a contribution to the overall normalisation uncertainty in the following analysis. No background subtraction is made.

Any $e^+e^- \to \gamma\gamma$ events in which both photons had converted would be rejected by the fourth selection cut. In order to estimate the number of such events, the photon conversion probability was calculated from the ratio of the observed number of $e^+e^- \to \gamma\gamma$ events with no photon conversion to the number with one photon conversion. These numbers are listed in table 2. The calculation was done separately for the barrel region ($|\cos\theta| < 0.80$) and for the endcap region ($0.80 < |\cos\theta| < 0.95$). Taking this conversion probability into account the total corrected number of $e^+e^- \to \gamma\gamma$ events is calculated to be 22.7. The conversion probability derived by this method has a large uncertainty, because it is based on very few events, and it is more than twice that expected from the known material in the detector. To account for this uncertainty we assign a systematic normalisation error of 6% to the corrected signal. Adding this in quadrature with the errors from the background determination and the luminosity measurement results in an overall normalisation uncertainty of 8.4%. Radiative corrections, complete to order α^3 [11], were applied to the data in order to obtain a lowest order total cross section, σ, which can easily be compared with the theoretical prediction and with results from other experiments. We measure $\sigma = 38.9 \pm 9.1$ pb for $|\cos\theta| < 0.95$ at $\sqrt{s} = 91.16$ GeV. The QED prediction is 42.5 pb. The cross sections for $|\cos\theta| < 0.95$ for the different centre of mass energy points are shown in figure 1a together with the QED prediction, which is proportional to $1/s$. The absolute value and the energy dependence of the total cross section are consistent with QED indicating no significant influence from the Z^0 resonance on the reaction $e^+e^- \rightarrow \gamma\gamma$.

The numbers of events in different polar angular bins are listed in table 3. The differential cross section for $e^+e^- \rightarrow \gamma\gamma$ is shown in figure 2, where the corrections for the conversion probability and radiative corrections have been applied to the data for each angular bin. The agreement between the data and the QED prediction is good. A deviation from QED can be parametrised by introducing cutoff parameters, $\Lambda_\pm$, into the electron propagator as follows [12].

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{s}\frac{1+\cos^2\theta}{1-\cos^2\theta}\left(1 \pm \frac{s^2}{2\Lambda_\pm^4}(1-\cos^2\theta)\right)$$

In order to obtain lower limits on $\Lambda_\pm$, the likelihood function L is defined as

$$L(\Lambda_\pm, N_L) = \frac{1}{\sqrt{2\pi}\Delta N_L}\exp\left(-\frac{1}{2}\left(\frac{1-N_L}{\Delta N_L}\right)^2\right)\prod_{i=1}^{5} P(N_i, \lambda_i(\Lambda_\pm, N_L))$$

where P denotes the Poisson distribution function and N_i and λ_i are the observed and the expected numbers of events for angular bin i. The overall normalisation factor, N_L, is allowed to vary with a standard deviation $\Delta N_L = 8.4\%$. Using this function we obtain lower limits of $\Lambda_+ > 82$ GeV and $\Lambda_- > 89$ GeV at 95% confidence level. Our limits are compared with previous limits [2] in table 4.

The differential cross section for $e^+e^- \rightarrow \gamma\gamma$ can be modified by the exchange of a virtual excited electron, e^*, of mass M_{e^*} and with coupling constant λ, where the effective Lagrangian is written as [12]

$$L_{eff} = \frac{\lambda e}{2M_{e^*}}\bar{e}\sigma_{\mu\nu}e^* F^{\mu\nu} + h.c.$$

In the limit $M_{e^*}^2 \gg s$, the cutoff parameter Λ_+ is related to the excited electron mass by the equation $M_{e^*}^2/\lambda = \Lambda_+^2$. In general, this relationship has been used by other experiments to set limits on M_{e^*}. For this analysis $M_{e^*}^2 \approx s$ and so we have used the full formula given in the appendix of reference [12]. Assuming $\lambda = 1$, we obtain a lower limit on the mass of the excited electron of 82 GeV at 95% confidence level. This is the same as the limit that would have been obtained if we had used the large M_{e^*} approximation. A similar limit has recently been set based on a direct search for excited electron production in Z^0 decays [13].

A possible deviation of the measured $e^+e^- \rightarrow \gamma\gamma$ cross section from the QED prediction could come from rare Z^0 decays such as $Z^0 \rightarrow \gamma\gamma$ (theoretically forbidden [1]) or $Z^0 \rightarrow \pi^0\gamma$ and $Z^0 \rightarrow \eta\gamma$, in which the neutral decay of an energetic π^0 or η particle fakes a single high energy photon. The event topology of these Z^0 decays is similar to that of the QED reaction $e^+e^- \rightarrow \gamma\gamma$ except for the angular distribution. The angular distribution of events arising from these Z^0 decays is predicted to be approximately proportional to $1+\cos^2\theta$ [4], whereas the QED reaction has a strong peak at small angles with respect to the beams. Therefore to set an upper limit on the branching ratios, only the barrel region ($|\cos\theta| < 0.8$) was used. The numbers of events observed in this region are listed in table 1 and the measured cross sections are shown in fig 1b for different centre of mass energies. The overall detection efficiencies are estimated to be 68%, 65% and 44% for the decays $Z^0 \rightarrow \gamma\gamma$, $Z^0 \rightarrow \pi^0\gamma$ and $Z^0 \rightarrow \eta\gamma$, respectively, where the geometrical acceptance, the conversion probability and the decay modes of the η have been taken into account. We assume that the cross section of $e^+e^- \to Z^0 \to X$ is given by a Breit-Wigner line shape with s-dependent width, convoluted with an initial state photon radiation function as described in [14]. The peak cross section, $\sigma_{\rm peak}$, is expressed as

$$\sigma_{\rm peak} = \frac{12\pi}{M_Z^2}\frac{\Gamma_{ee}\Gamma_X}{\Gamma_Z^2}$$

where M_Z and Γ_Z are the mass and the total width of the Z^0 and Γ_{ee} and Γ_X are the partial decay widths of $Z^0 \to e^+e^-$ and $Z^0 \to X$. We define the likelihood function L as

$$L(\Gamma_X, N_L) = \frac{1}{\sqrt{2\pi}\Delta N_L}\exp\left(-\frac{1}{2}\left(\frac{1-N_L}{\Delta N_L}\right)^2\right)\prod_{i=1}^{11} P(N_i, \lambda_i(\Gamma_X, N_L))$$

where N_i and λ_i are the observed and the expected numbers of events for the centre of mass energy bin i and P, N_L and ΔN_L have the same meanings as before. The contributions from QED and from $Z^0 \to X$ are summed in calculating λ_i. Using this function with our measured values of M_Z, Γ_Z and Γ_{ee} [7], we determined upper limits on $\Gamma_{\gamma\gamma}$, $\Gamma_{\pi^0\gamma}$ and $\Gamma_{\eta\gamma}$ to be 0.94 MeV, 0.99 MeV and 1.46 MeV, respectively, at 95% confidence level. These limits correspond to $Br(Z^0 \to \gamma\gamma) < 3.7 \times 10^{-4}$, $Br(Z^0 \to \pi^0\gamma) < 3.9 \times 10^{-4}$ and $Br(Z^0 \to \eta\gamma) < 5.8 \times 10^{-4}$.

Events of the higher order QED process $e^+e^- \to \gamma\gamma\gamma$ were selected according to the following criteria.

i) The number of electromagnetic clusters with energies more than 0.2 GeV is required to be less than 9.

ii) Three energetic electromagnetic clusters are required, each with an energy larger than 10% of the beam energy and $|\cos\theta| < 0.95$.

iii) The opening angles between any two energetic clusters should be larger than 20°.

iv) The sum of the three opening angles should be larger than 350°, to ensure that the event is planar.

v) At least two of the three energetic clusters should be isolated from any charged track by more than 10° either in azimuthal or polar angles. This cut rejects most of the $e^+e^- \to e^+e^-\gamma$ events.

The number of selected events was two : one is observed at $\sqrt{s}$ = 88.28 GeV and the other at $\sqrt{s}$ = 91.53 GeV. The two events were visually scanned and confirmed as clear $e^+e^- \to \gamma\gamma\gamma$ events. The expected number of events is 0.72, calculated by the Monte Carlo program [11]. The probability of observing 2 events is 12.6%.

A possible enhancement to the process $e^+e^- \to \gamma\gamma\gamma$ could come from the decay $Z^0 \to \gamma\gamma\gamma$. The branching ratio $Br(Z^0 \to \gamma\gamma\gamma)$ is 3×10^{-10} in the standard model [15], but it may be of order 2×10^{-4} in some composite models [5]. The overall detection efficiency for the $Z^0 \to \gamma\gamma\gamma$ decay is estimated to be 67% by a Monte Carlo simulation, including the geometrical acceptance. The upper limit on the decay width of $Z^0 \to \gamma\gamma\gamma$ was obtained in a similar way to that on the width of $Z^0 \to \gamma\gamma$. The upper limit is determined to be 0.72 MeV at 95% confidence level, which corresponds to an upper limit of 2.8×10^{-4} on the branching ratio $Br(Z^0 \to \gamma\gamma\gamma)$.

In summary, we have measured the total and differential cross section of the reaction $e^+e^- \to \gamma\gamma$ at centre of mass energies around the Z^0 mass. Our measurement is in good agreement with the QED prediction. The lower limits on the cutoff parameters of the modified electron propagator are $\Lambda_+ > 82$ GeV and $\Lambda_- > 89$ GeV. The lower limit on the mass of an excited electron is 82 GeV, assuming the coupling constant $\lambda = 1$. No influence of the Z^0 boson is observed and the upper limits on the branching ratios $Br(Z^0 \to \gamma\gamma)$, $Br(Z^0 \to \pi^0\gamma)$ and $Br(Z^0 \to \eta\gamma)$ were found to be 3.7×10^{-4}, 3.9×10^{-4} and 5.8×10^{-4}, respectively. Two events from the higher order process $e^+e^- \to \gamma\gamma\gamma$ were observed, consistent with the QED prediction. The upper limit on the branching ratio $Br(Z^0 \to \gamma\gamma\gamma)$ was determined to be 2.8×10^{-4}. All the limits are obtained at 95% confidence level.

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Tables

$\sqrt{s}$ (GeV)	$L_{\rm int}$ ($\rm nb^{-1}$)	$N^{\rm obs}_{\gamma\gamma}$ $\lvert\cos\theta\rvert < 0.95$	$N^{\rm obs}_{\gamma\gamma}$ $\lvert\cos\theta\rvert < 0.80$	$N^{\rm exp}_{\gamma\gamma}$ $\lvert\cos\theta\rvert < 0.95$	$N^{\rm exp}_{\gamma\gamma}$ $\lvert\cos\theta\rvert < 0.80$
88.28	66.2 ± 1.2	2	1	2.3	1.2
89.28	38.9 ± 1.0	0	0	1.3	0.7
90.28	60.6 ± 1.2	3	2	2.1	1.0
91.03	128.7 ± 1.8	3	1	4.3	2.2
91.28	127.8 ± 1.8	7	3	4.2	2.2
91.53	109.4 ± 1.6	2	1	3.6	1.8
92.28	49.6 ± 1.1	1	1	1.6	0.8
92.56	5.3 ± 0.4	0	0	0.2	0.1
93.28	76.1 ± 1.4	3	1	2.4	1.2
94.28	8.4 ± 0.5	0	0	0.3	0.1
95.04	12.9 ± 0.6	0	0	0.4	0.2
91.16	684.0 ± 4.1	21	10	22.7	11.5

Table 1: The centre of mass energies, $\sqrt{s}$, the integrated luminosities, $L_{\rm int}$, numbers of events observed, $N^{\rm obs}_{\gamma\gamma}$, and numbers of events expected, $N^{\rm exp}_{\gamma\gamma}$. The errors on the luminosity values are statistical only; there is an additional systematic error of 2.2%. The numbers of events are given for polar angular regions $\lvert\cos\theta\rvert < 0.95$ and $\lvert\cos\theta\rvert < 0.80$. The conversion probability and radiative corrections have been taken into account in the expectation.

$\lvert\cos\theta\rvert$	N_0	N_1	N_{tot}
0.00-0.80	6	4	10.7
0.80-0.95	6	5	12.0

Table 2: The numbers of $e^+e^- \to \gamma\gamma$ events with no photon conversion, N_0, and with one photon conversion, N_1, and the total number of $e^+e^- \to \gamma\gamma$ events after correction for the conversion probability, N_{tot}. The calculation was done separately for the barrel region ($\lvert\cos\theta\rvert < 0.8$) and the endcap region ($0.80 < \lvert\cos\theta\rvert < 0.95$).

$\lvert\cos\theta\rvert$	$N^{\rm obs}_{\gamma\gamma}$	$N^{\rm exp}_{\gamma\gamma}$
0.00-0.20	1	1.6
0.20-0.40	4	2.1
0.40-0.60	3	2.7
0.60-0.80	2	5.2
0.80-0.95	11	11.4

Table 3: The $\lvert\cos\theta\rvert$ range, numbers of events observed, $N^{\rm obs}_{\gamma\gamma}$, and numbers of events expected, $N^{\rm exp}_{\gamma\gamma}$. The conversion probability and radiative corrections have been taken into account in the expectation.

Experiment	Λ_+ (GeV)	Λ_- (GeV)
OPAL (this experiment)	82	89
CELLO	59	44
JADE	61	57
MARK J	72	
PLUTO	46	
TASSO	61	56
HRS	59	59
MAC	66	67
AMY	65	
TOPAZ	94	59

Table 4: Comparison of lower limits on the cutoff parameters of the modified electron propagator $\Lambda_\pm$. The limits were obtained at 95% confidence level.

Figure Captions

Figure 1: The measured total cross section for $e^+e^- \rightarrow \gamma\gamma$ (points with error bars), compared with the QED prediction (solid curve), within the polar angular ranges a) $|\cos\theta| < 0.95$ and b) $|\cos\theta| < 0.80$. The average cross section is shown by a square with an error bar. Corrections for the conversion probability and radiative corrections have been applied to the data. In b) the dashed curve shows the expectation for $\Gamma_{\gamma\gamma} = 0.94$ MeV (95% confidence level limit).

Figure 2: The measured differential cross section for $e^+e^- \rightarrow \gamma\gamma$ (points with error bars). Corrections for the conversion probability and radiative corrections have been applied for each bin. The solid curve shows the QED prediction. The dashed curves show the expectations with the cutoff parameters $\Lambda_+ = 82$ GeV and $\Lambda_- = 89$ GeV (95% confidence level limits).

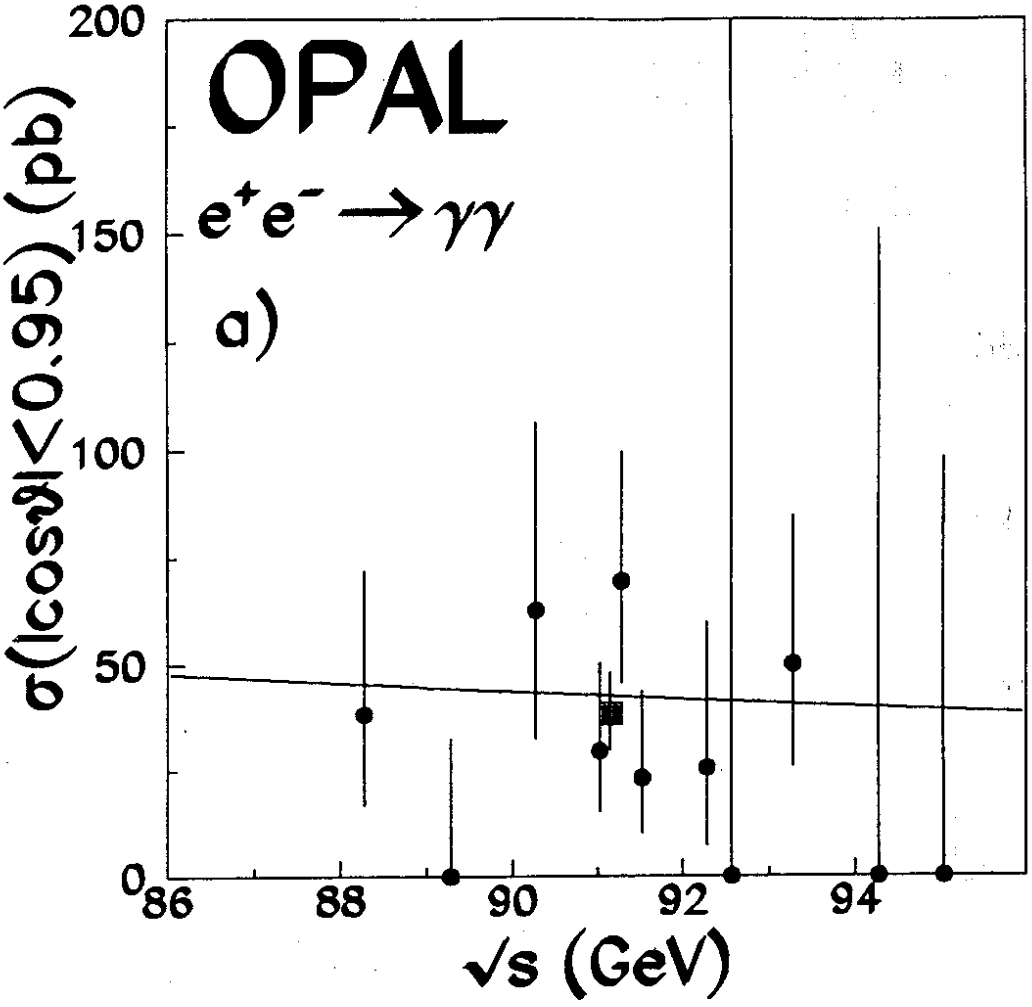
OPAL
$e^+e^- \rightarrow \gamma\gamma$
a)
$\sigma(|\cos\vartheta|<0.95)$ (pb)
0
50
100
150
200
86
88
90
92
94
$\sqrt{s}$ (GeV)

FIG. 1a

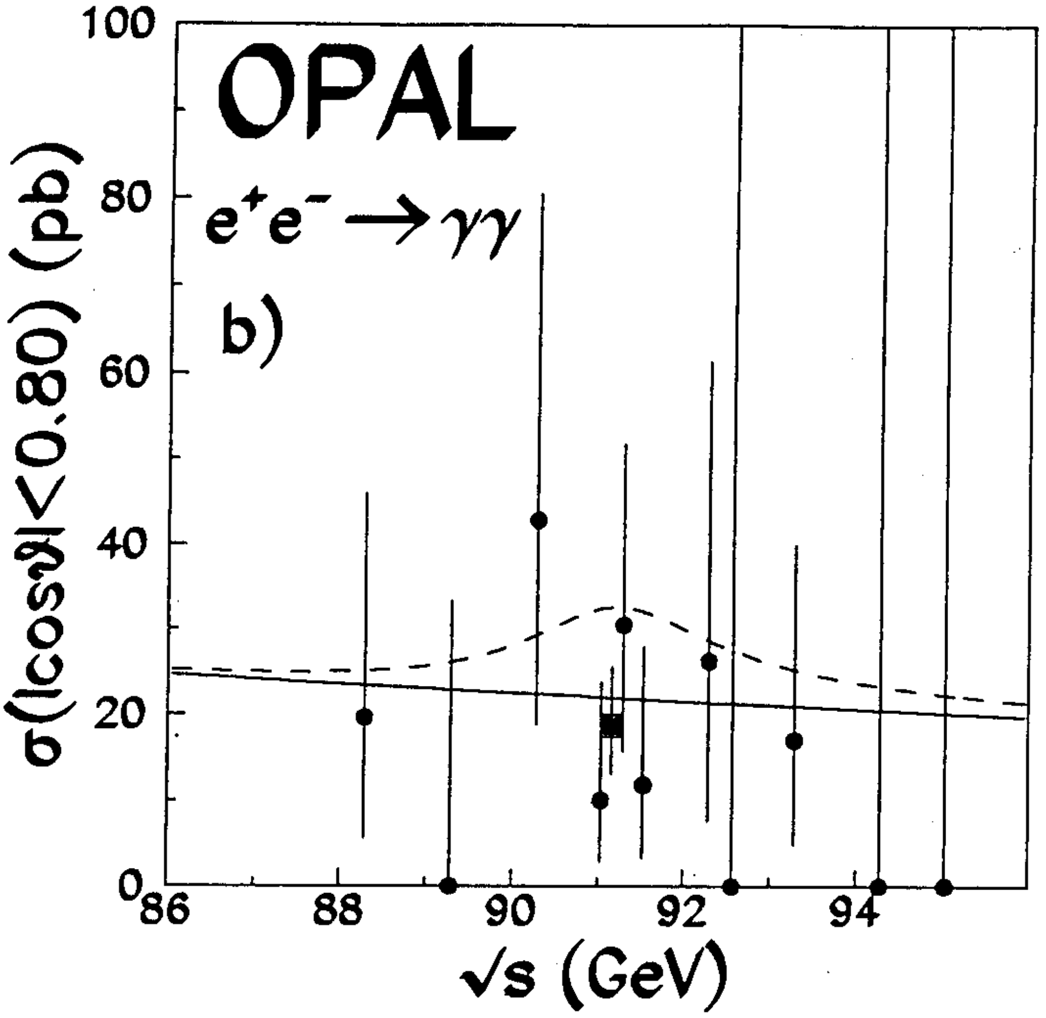
OPAL
$e^+e^- \rightarrow \gamma\gamma$
b)
$\sigma(|\cos\vartheta|<0.80)$ (pb)
100
80
60
40
20
0
86
88
90
92
94
$\sqrt{s}$ (GeV)

FIG. 1b

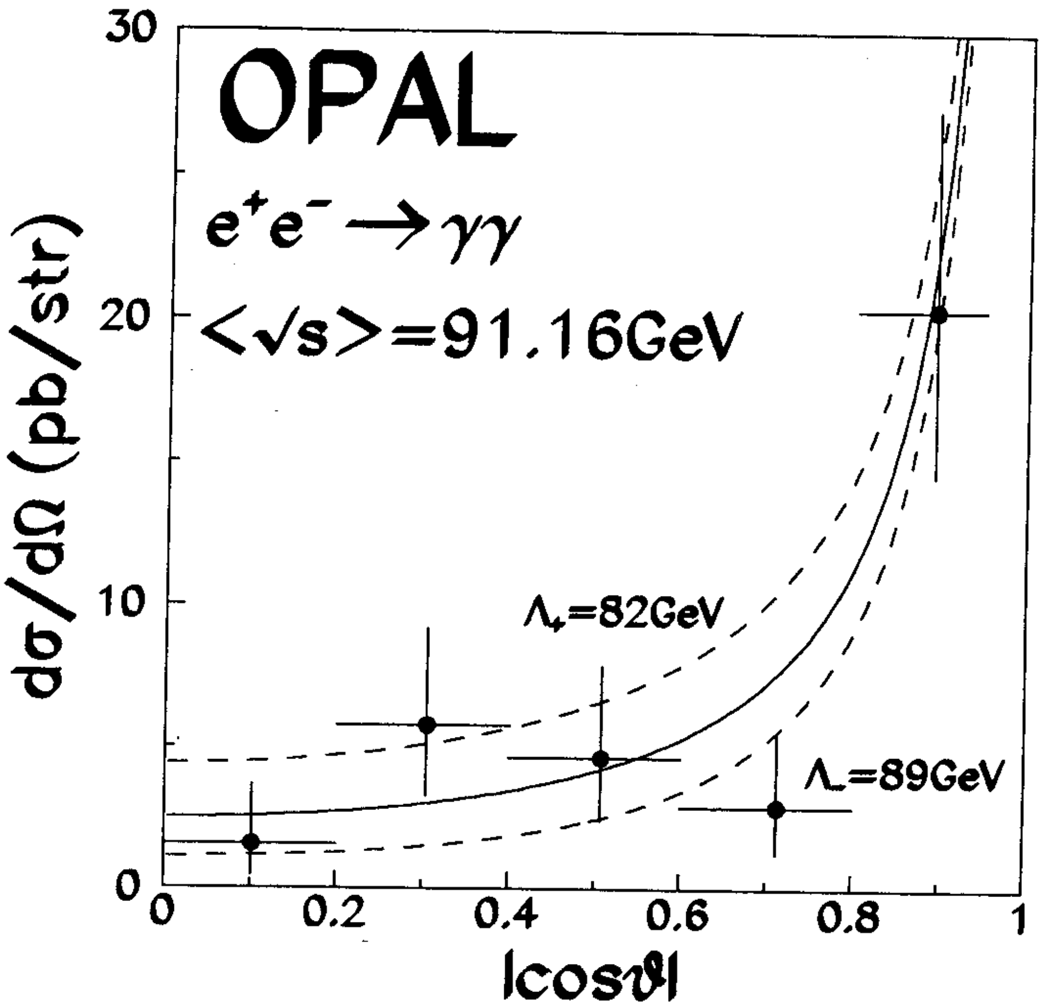
OPAL
$e^+e^- \rightarrow \gamma\gamma$
$<\sqrt{s}>=91.16$GeV
$\Lambda_+=82$GeV
$\Lambda_-=89$GeV
dσ/dΩ (pb/str)
|cosϑ|
30
20
10
0
0
0.2
0.4
0.6
0.8
1

FIG. 2