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A test of quantum electrodynamics in the reaction $e^+e^- \to \gamma\gamma(\gamma)$

L3 Collaboration

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We have measured the total and differential cross sections of the reaction $e^+e^- \to \gamma\gamma(\gamma)$ at center-of-mass energies around 91 GeV, with an integrated luminosity of 14.2 pb^{-1}. The results are in good agreement with QED predictions. We set lower limits, at 95% confidence level, on the QED cutoff parameters of $\Lambda_+ > 139$ GeV, $\Lambda_- > 108$ GeV and on the mass of an excited electron of $m_{e^*} > 127$ GeV. We searched for Z^0 rare decays with photonic signatures in the final state. Upper limits, at 95% confidence level, for the branching ratio of Z^0 decaying into $\pi^0\gamma/\gamma\gamma$, $\eta\gamma$ and $\gamma\gamma\gamma$ are 1.2×10^{-4}, 1.8×10^{-4}, 3.3×10^{-5} respectively.

1. Introduction

Quantum electrodynamics (QED) is the best tested theory in physics; so far no deviation has been found even at small distances. The reaction $e^+e^- \to \gamma\gamma(\gamma)$ is a pure QED process and can test breakdown effects. QED breakdown would imply that the electron has a finite size [1–3]. In particular an excited electron might exist which couples to electrons and photons with a magnetic interaction: $(e\lambda/2m_{e^*})\overline{\psi_{e^*}}\sigma_{\mu\nu}\psi_e F^{\mu\nu}$ where m_{e^*} is the mass of the excited electron, λ the coupling constant and $F^{\mu\nu}$ the electromagnetic field tensor [2]. This interaction is gauge invariant but is not renormalizable and the effect of such a breakdown

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has been parametrized [1,2]. The total differential cross section at the Born level, $(d\sigma/d\Omega)^0_T$, can be written as:

$$(d\sigma/d\Omega)^0_T \equiv \sigma(\theta)^0_T = \sigma(\theta)^0_{QED}\ (1 \pm \delta_{new}),$$

where $\delta_{new} = s^2/2\ (1/\Lambda^4_\pm)\ (1-\cos^2\theta)$, θ is the angle of the emitted photons with respect to the beam axis, $\sqrt{s}$ the center-of-mass energy and $\Lambda_\pm$ the QED cut-off parameters.

The reaction $e^+e^- \to \gamma\gamma(\gamma)$ can also be used to search for forbidden or rare Z^0 decays with photons in the final state. Since Z^0 is a spin 1 boson it is not allowed to decay into two photons [4]. Some models predict a coupling of Z^0 to $\pi^0\gamma$ or $\eta\gamma$ [5]. The decay of Z^0 to three photons has a branching ratio in the standard model of about 7×10^{-10} [6]. However in some compositeness models branching ratios as high as 10^{-4} are predicted [7,8].

We have previously published the results of the reaction $e^+e^- \to \gamma\gamma(\gamma)$ based on 32 events [9]. Similar results have been published by other experiments [12]. With our latest data, corresponding to an integrated luminosity of 14.2 pb^{-1} and an improved acceptance, we have increased the statistics by an order of magnitude.

2. The L3 detector

The L3 detector [10] consists of a central tracking chamber (TEC), a forward-backward tracking chamber (FTC), a high resolution electromagnetic calorimeter composed of bismuth germanium oxide (BGO) crystals with a barrel region and endcaps to cover the forward-backward solid angle down to 10°, a ring of scintillation counters, a uranium and brass hadron calorimeter with proportional wire chamber readout (which also comprises a barrel and forward-backward endcaps) and a high precision muon spectrometer. These detectors are located in a 12m diameter magnet which provides a uniform field of 0.5 T along the beam direction. Forward BGO arrays, on either side of the detector, measure the luminosity by detecting small angle Bhabha events.

The forward–backward tracking chamber and the BGO endcaps were not installed until 1991 and as a consequence 1990 data are limited to the barrel region $44° < \theta < 136°$. With the BGO endcaps and the FTC, we use data collected in the angular range $14° < \theta < 166°$ covering 97% of the full solid angle.

3. Event selection

To select a $\gamma\gamma(\gamma)$ event we required:
(1) At least 70% of the center-of-mass energy to be in the BGO.
(2) The number of clusters in the BGO to be less than 9.
(3) The acollinearity angle between the two most energetic clusters to be less than 25°.
(4) No tracks detected inside TEC and FTC.

Cuts 1 and 2 eliminate all hadronic events and leave 1.2% $\tau^+\tau^-$ background, which is removed by cut 4. Cut 3 eliminates mainly cosmic ray background and low multiplicity noise events. Bhabha events, $e^+e^- \to e^+e^-(\gamma)$, constitute the main background which contaminates our data sample when both tracks remain undetected in the TEC and FTC. The probability to detect at least one of the two tracks, the veto efficiency, is measured for both the TEC and the FTC using Bhabha events with either one or two detected tracks. We used our hadronic sample to monitor the TEC performance and to exclude periods with low efficiency. Consequently the luminosity had to be corrected according to the number of hadronic events remaining in the data. Combining tracking information from the TEC ($|\cos(\theta)| < 0.883$) and the FTC ($0.883 < |\cos(\theta)| < 0.97$), we reach a veto efficiency of 99.98% ± 0.02%. With the above cuts we selected 426 candidates for an $e^+e^- \to \gamma\gamma(\gamma)$ reaction. The contamination from Bhabha background is estimated to be less than 3 events.

A special selection was performed for the three photon final state events. Keeping the previous cuts 1,2 and 4, we added the following ones:
(1) There must be at least 3 clusters in the BGO.
(2) The energy of the least energetic cluster must exceed 3 GeV.
(3) The angle in space between any two clusters must be larger than 25°.
(4) The sum of the angles in space between clusters must be more than 350°, thus ensuring that the event is highly coplanar.

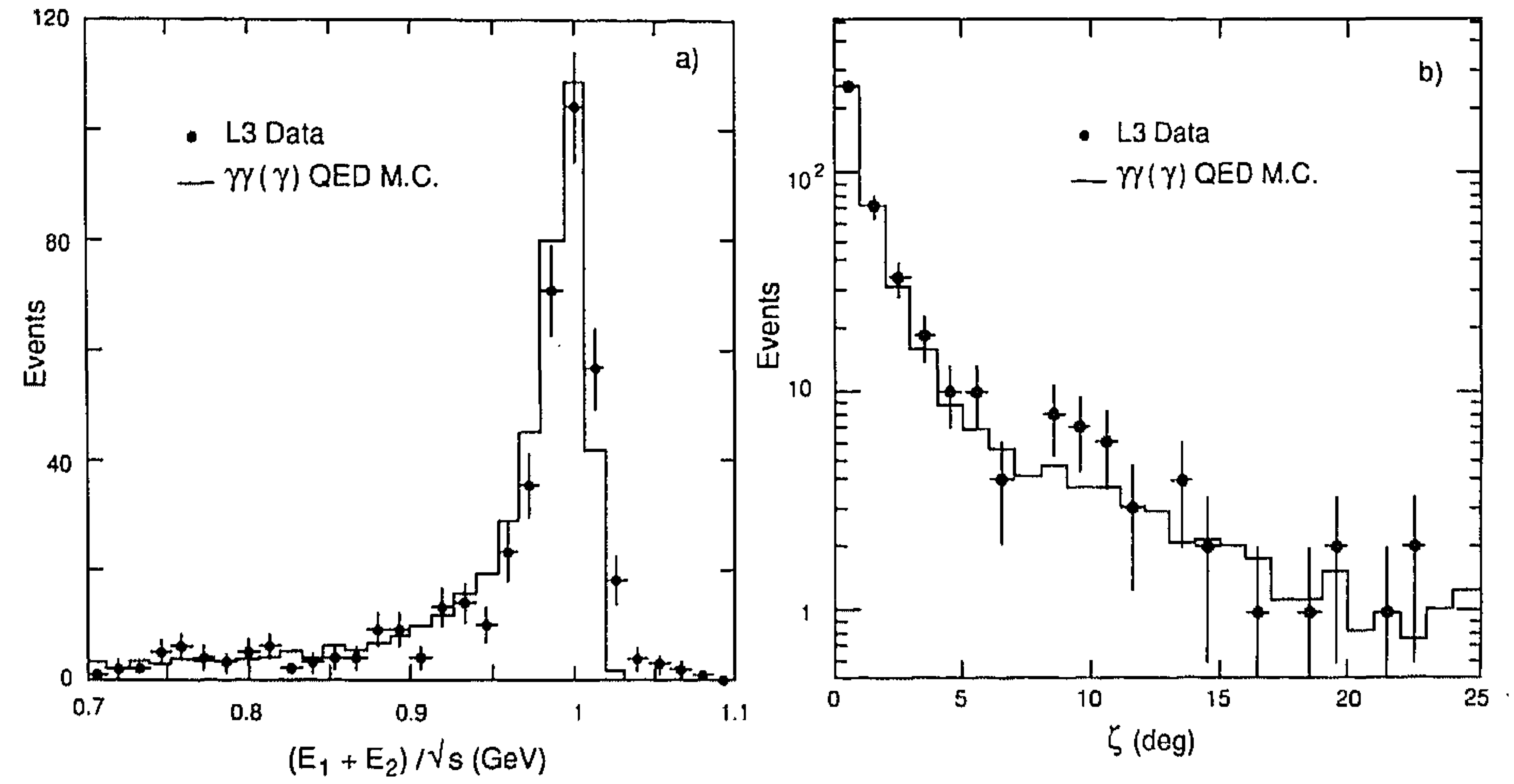

Fig. 1. (a) The sum of energies of the first and second most energetic photons divided by the center-of-mass energy. (b) The acolinearity angle ζ, between the two most energetic photons.

With the above cuts we selected 10 $e^+e^- \to \gamma\gamma\gamma$ candidates.

4. Analysis

To take into account radiative corrections we used the Berends and Kleiss QED Monte Carlo [11] which includes virtual photon corrections, soft and hard bremsstrahlung to $O(\alpha^3)$. Fig. 1a shows a comparison, between data and Monte Carlo, of the sum of energies of the two most energetic clusters normalized to the beam energy. Fig. 1b shows a similar comparison for the acollinearity angle ζ, between the two most energetic clusters. The efficiency for selecting events with photons in the final state distributed according to the QED prediction was found to be 64% ± 3% in the angular range $14° < \theta < 166°$ and 90% ± 1% for $44° < \theta < 136°$. Losses from photon conversions, most significant in the forward–backward region, and from gaps in the detector are included. The trigger efficiency is more than 99.9%. The integrated luminosity for the different center-of-mass energies is given in table 1. This table also shows the number of events for the 1990 and 1991 data runs and the total measured cross sections. The 1991 cross sections are also shown in fig. 2 as a function of the center-of-mass energy.

In table 2 we give the measured differential cross sections for $e^+e^- \to \gamma\gamma(\gamma)$. Fig. 3a shows the data

Table 1
The upper part shows the integrated luminosities as a function of the center-of-mass energies for the 1991 data ($14° < \theta < 166°$). Also given are the number of events observed and the total measured cross sections. The 1990 data ($44° < \theta < 136°$) are shown in the lower part. The first and last three energy bins have been combined.

	$\sqrt{s}$ (GeV)	$\mathcal{L}_{int}$ (pb^{-1})	$N_{\gamma\gamma(\gamma)}$	σ_{meas} (pb)
1991	88.5	0.20	2	–
	89.4	0.59	15	40.2 ± 10.4
	90.3	0.47	24	80.4 ± 16.4
	91.2	7.52	278	58.0 ± 3.5
	92.0	0.38	11	45.1 ± 13.5
	93.0	0.72	25	54.5 ± 10.9
	93.7	0.53	14	41.8 ± 11.2
1990	89.8	0.53	5	10.5 ± 4.7
	91.2	2.59	43	18.4 ± 2.8
	92.6	0.65	9	15.4 ± 5.1

points compared to the Born level and to the radiatively corrected QED cross section. We note that radiative corrections decrease the Born QED cross section in the barrel region while increasing it in the forward–backward region. The χ^2 of the data points compared to the QED expectation is 12.3 for 9 degrees of freedom, indicating that the measured differential cross section is in agreement with the QED prediction.

A possible QED breakdown has been parametrized

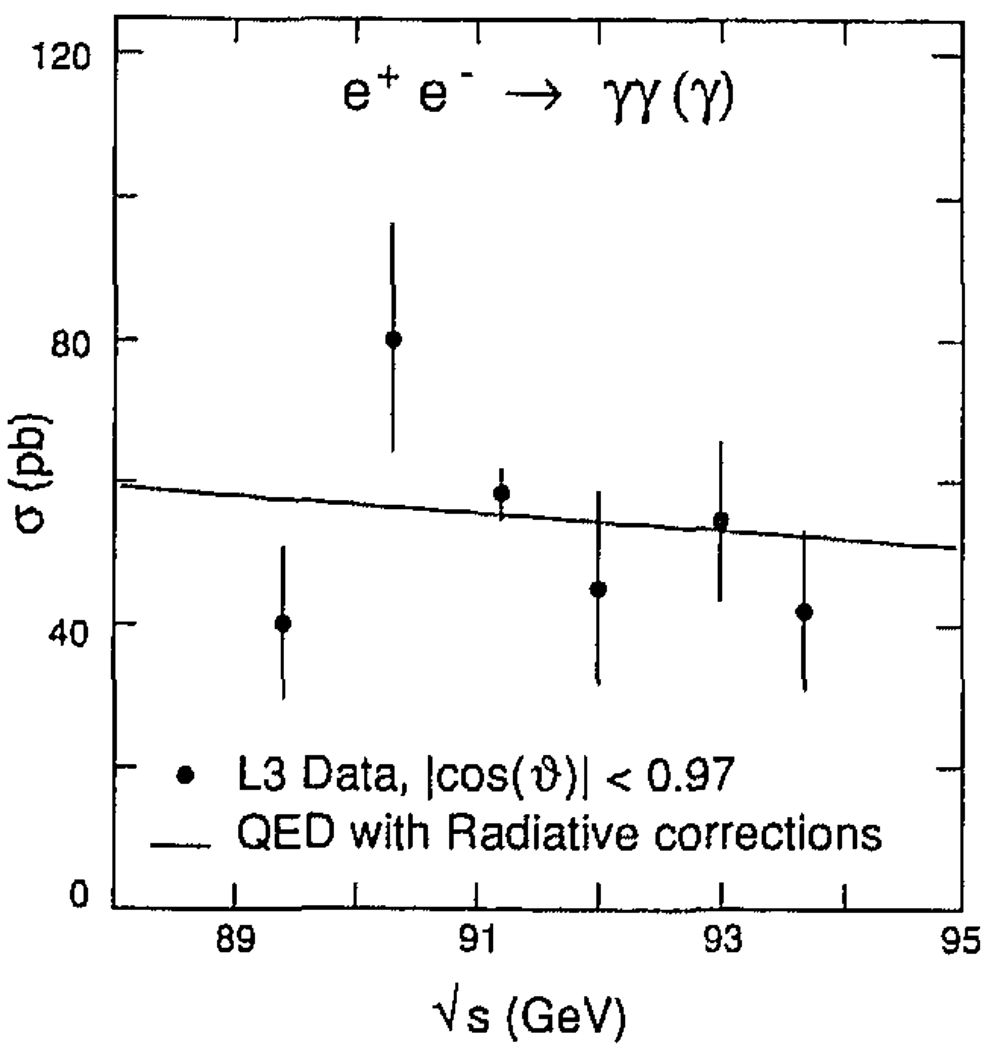

Fig. 2. Total measured cross section as a function of the center-of-mass energy for the angular region $14° < \theta < 166°$. QED includes virtual and radiative corrections to $O(\alpha^3)$.

in the differential cross section at Born level. As mentioned in the introduction the lagrangian describing the coupling of an excited electron to a photon and an electron is gauge invariant but not renormalizable. As a consequence radiative corrections for the diagram involving the excited electron have not yet been calculated. Combining the QED contribution with corrections up to $O(\alpha^3)$ with the zeroth-order contribution of the excited electron leads to a differential cross section that is infrared divergent. The measured cross section compared to the theoretical one calculated to $O(\alpha^3)$ is:

Table 2
Differential cross sections as a function of $|\cos\theta|$ at $\sqrt{s}$ = 91.2 GeV. The $|\cos\theta|$ values given in the first column are event-weighted averages; the second column gives the number of events. Data from 1990 ($44° < \theta < 136°$) and 1991 ($14° < \theta < 166°$) have been combined.

$\lvert\cos\theta\rvert$	$N_{\gamma\gamma(\gamma)}$ (1990+1991)	$(d\sigma_{meas}/d\Omega_{\gamma\gamma(\gamma)})$ (pb/sr) (1990+1991)
0.077	13	1.8 ± 0.5
0.177	23	3.3 ± 0.7
0.299	25	3.5 ± 0.7
0.435	18	2.6 ± 0.6
0.550	29	4.1 ± 0.8
0.658	52	8.2 ± 1.1
0.852	48	23.0 ± 3.3
0.906	38	28.2 ± 4.6
0.954	75	56.3 ± 6.5

$$\sigma(\theta)_{meas} = \sigma(\theta)_{QED}^{O(\alpha^3)} (1 + \rho),$$

where ρ is a measure of a possible QED breakdown. We approximated the infrared divergent differential cross section by a finite measurable one, replacing ρ by its Born level expression:

$$\rho \approx \left[\sigma(\theta)_T^0 - \sigma(\theta)_{QED}^0\right] / \sigma(\theta)_{QED}^0 = \delta_{new},$$

with δ_{new} as defined in the introduction. In this approach the data are directly compared to the theory.

We used the unbinned maximum likelihood method to set lower limits on the breakdown parameters and on the mass of an excited electron. The probability

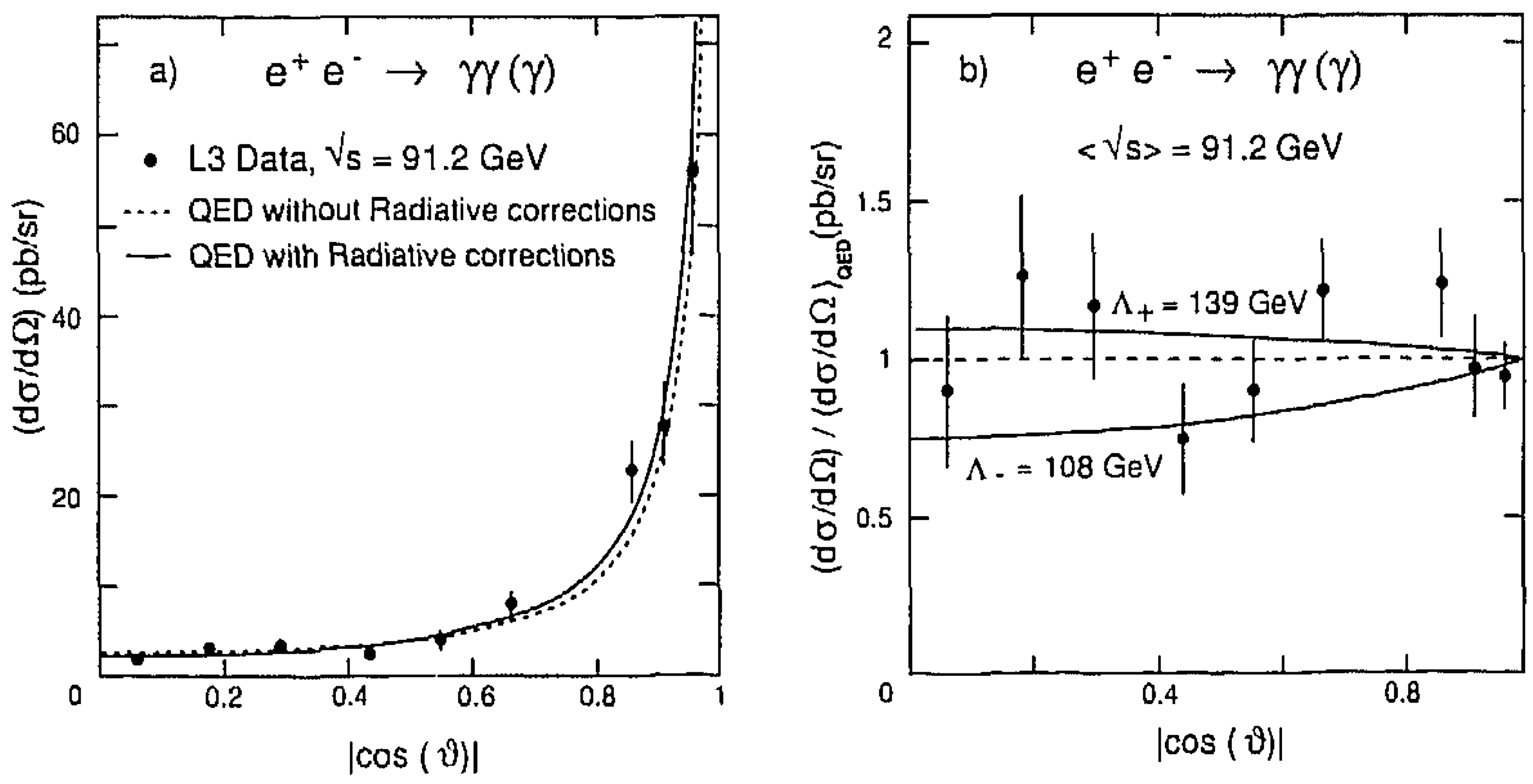

Fig. 3. (a) Measured differential cross section. The solid line gives the QED differential cross section to $O(\alpha^3)$; the dashed line the zero-order QED differential cross section. (b) Ratio of measured to QED differential cross sections. We superimpose the same ratio with contributions from QED to $O(\alpha^3)$ and from Λ_+, Λ_- using the lower limits found.

function was constructed by normalizing the differential cross section given above to the total cross section in our acceptance. The likelihood function is:

$$\mathcal{L} = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{-(N_{\rm obs} - N(\Lambda))^2}{2\sigma^2}\right) \times \prod_{i=1}^{N_{\rm obs}} P(\theta_i, \Lambda),$$

where Λ is the parameter under consideration, $N_{\rm obs}$ the observed number of events, $N(\Lambda)$ the expected number of events, and $P(\theta_i, \Lambda)$ the event probability density depending on the parameter Λ and the polar event angle θ_i. The first term corresponds to the overall normalization constraint. The error σ on the number of expected events includes in quadrature the statistical error and a systematic error of 3%. At 95% confidence level we found $\Lambda_+ > 139$ GeV, $\Lambda_- > 108$ GeV. To fit the mass of the excited electron we used the full expression for the differential cross section given in ref. [2], assuming the coupling constant $\lambda = 1$. The same likelihood function was used as for Λ_+ and Λ_-. At 95% confidence level we found $m_{e^*} > 127$ GeV. Fig. 3b shows the ratio of measured to QED differential cross section. The solid curves illustrate the effect of Λ_+ and Λ_- on the QED prediction.

We searched for decays of $Z^0 \to \pi^0\gamma$, $Z^0 \to \eta\gamma$, $Z^0 \to \gamma\gamma$. To calculate the selection efficiency for these channels we used a $\pi^0\gamma$, $\eta\gamma$ Monte Carlo event simulation with particle angular distribution $(1 + \cos^2\theta)$. The $\pi^0\gamma$, $\gamma\gamma$ decay modes leave the same photonic signature in the detector and the total acceptance for both was found to be 73%. The case of $Z^0 \to \eta\gamma$ is different because we only considered the decays of η into either $3\pi^0$ or 2γ which accounts for 71% of its decay products. The total acceptance for $Z^0 \to \eta\gamma$ was therefore found to be 52%. Table 3 lists the various processes and the total acceptances for the 1990 and 1991 data. In general the Born cross section at the Z^0 peak for the reaction $Z^0 \to X$ is given by:

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

where Γ_{ee} is the electronic width of the Z^0, Γ_Z the total Z^0 width and Γ_X the width of the rare decay mode under consideration. For the variation of the cross section with the center-of-mass energy we used a Breit Wigner formula with energy dependent width:

Table 3
The acceptance×efficiency for the various processes in the two angular regions considered; the systematic error is 3%.

Process	Acceptance×efficiency	
	$44° < \theta < 136°$	$14° < \theta < 166°$
$Z^0 \to \pi^0\gamma$, $\gamma\gamma$	0.57	0.73
$Z^0 \to \eta\gamma$	0.40	0.52
$Z^0 \to \gamma\gamma\gamma$	0.30	0.49

$$\sigma_s = \sigma_{\rm peak} \frac{s\Gamma_Z^2}{(s - m_Z^2)^2 + (s\Gamma_Z/m_Z)^2}.$$

For Γ_{ee}, Γ_Z and m_Z we used our measured values of ref. [13]. The likelihood constructed uses Poisson statistics to compare for every center-of-mass energy bin the observed and the expected number of events (contributions from QED to $O(\alpha^3)$ and from the Z^0 rare decays):

$$\mathcal{L} = \prod_{i=1}^{6} P(N_i, N_{\rm exp}(\Gamma_X)),$$

where N_i is the observed number of events for energy bin 'i' and $N_{\rm exp}$ is the expected number for that energy bin. A systematic error of 3% was taken into account. With this likelihood function we obtain at 95% confidence level the following upper limits:

$$\Gamma(Z^0 \to \eta\gamma) < 0.44 \text{ MeV or}$$
$$\text{BR}(Z^0 \to \eta\gamma) < 1.8 \times 10^{-4},$$
$$\Gamma(Z^0 \to \pi^0\gamma/\gamma\gamma) < 0.31 \text{ MeV or}$$
$$\text{BR}(Z^0 \to \pi^0\gamma) < 1.2 \times 10^{-4}.$$

In composite models the Z^0 may couple to photons through its charged constituents [8]. The three photons in the final state coming from a Z^0 decay may be separated from the QED process $e^+e^- \to \gamma\gamma\gamma$ through their distinct topology. For example the energy of the least energetic photon for a QED event is preferentially low and it is emitted in the forward–backward direction. The cuts for three photon selection have been given above. We found 10 events at all center-of-mass energies and from QED we expect 12 $e^+e^- \to \gamma\gamma\gamma$ events. Fig. 4 shows the energy of the least energetic photon versus its angle with respect to the beam axis. We note here that the anomalous

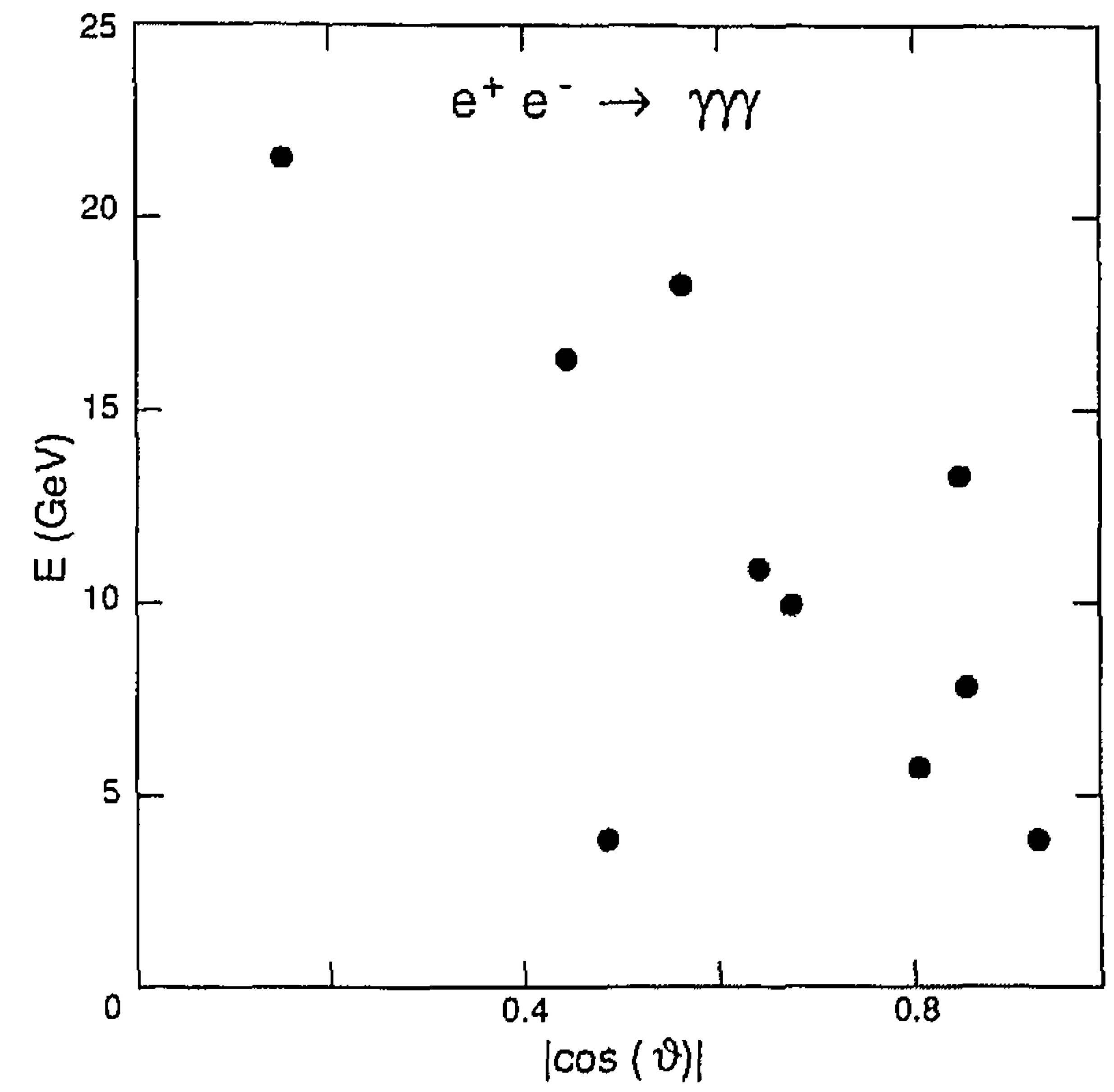

Fig. 4. The energy of the least energetic photon versus its angle with respect to the beam axis.

term which couples Z^0 to photons has negligible effect away from the Z^0 pole [8] and we therefore only considered events on the Z^0. The efficiency was calculated using an analytical calculation [8] which provides the $Z^0 \to \gamma\gamma\gamma$ cross section. The total acceptance was found to be 49%. We found 5 events on the Z^0 peak whereas from QED we expect 8.6. Using Poisson statistics and allowing for background, we set an upper limit on the branching ratio for the reaction $Z^0 \to \gamma\gamma\gamma$ of $BR(Z^0 \to \gamma\gamma\gamma) < 3.3 \times 10^{-5}$.

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