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We have measured the cross-section of the reaction $e^+e^-\to\gamma\gamma$ at center of mass energies around the Z^0 mass. The results are in good agreement with QED predictions. For the QED cutoff parameters the limit of $\Lambda_+ > 103$ GeV and $\Lambda_- > 118$ GeV are found. For the decays $Z^0\to\gamma\gamma$, $Z^0\to\pi^0\gamma$, $Z^0\to\eta\gamma$ and $Z^0\to\gamma\gamma\gamma$ we find upper limits of 2.9×10^{-4}, 2.9×10^{-4}, 4.1×10^{-4} and 1.2×10^{-4}, respectively. All limits are at 95% CL.

1. Introduction

At LEP energies, the reaction $e^+e^-\to\gamma\gamma$ provides a clean test of QED. In contrast to lepton pair production it is in lowest order not affected by weak interaction effects and hadronic vacuum polarisation. In the absence of rare or theoretically forbidden decays, such as $Z^0\to\gamma\gamma$, this reaction can only proceed via the exchange of a virtual electron. On the other hand, deviations from QED in the Z^0 region, could yield information on non-standard-model properties of this boson.

The first order differential cross section for $e^+e^-\to\gamma\gamma$ is predicted by the Born term of QED. Deviations from QED are generally parametrized by introducing cutoff parameters $\Lambda_\pm$, i.e. by generalizing the lowest order QED differential cross section to [1–3]

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

At LEP energies higher order terms are important, however, and radiative corrections [4] are necessary before comparing the above expression with data. We report here on a comparison between our data on $e^+e^-\to\gamma\gamma$ obtained in the Z^0 region and the QED prediction for this reaction calculated up to order α^3.

The same reaction $e^+e^-\to\gamma\gamma$ can also be used to set limits for the mass of an excited virtual electron (e^*) [3] and various forbidden or rare Z^0 decay modes.

2. The L3 detector

The L3 detector covers 99% of 4π. The detector in-

[1] Supported by the German Bundesministerium für Forschung und Technologie.

cludes a central vertex chamber, a precise electromagnetic calorimeter composed of BGO crystals, a uranium and brass hadron calorimeter with proportional wire chamber readout, a high accuracy muon chamber system, and a ring of scintillation counters. These detectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 T along the beam direction. The luminosity is determined by measuring small angle Bhabha events in two forward calorimeters consisting of BGO crystals. A detailed description of each detector subsystem, and its performance, is given in ref. [5].

The fine segmentation of the electromagnetic calorimeter allows the measurement of photon and electron showers with an angular resolution of 2 mrad. For the present analysis we only use data collected in the polar angle θ region:

$$\tfrac{1}{4}\pi < \theta < \tfrac{3}{4}\pi .$$

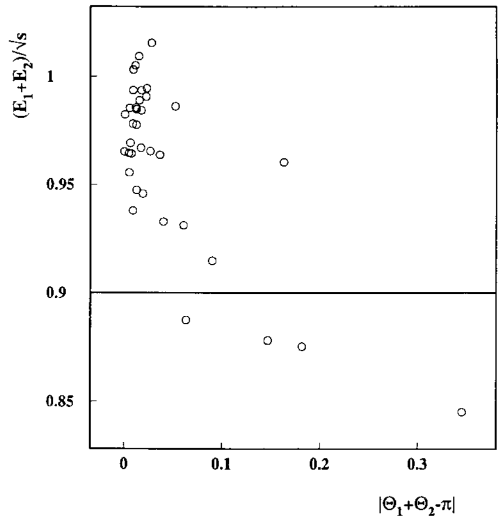

Fig. 1. The $\gamma\gamma$ energy sum versus $|\theta_1+\theta_2-\pi|$ with the solid line showing the energy cut $E_1+E_2>0.9\sqrt{s}$.

3. Event selection

Events collected from the 1990 LEP running period (March–June) corresponding to 2.24 pb^{-1} are used for the present analysis.

The selection of the $e^+e^-\to\gamma\gamma$ candidates is primarily based on the number of shower peaks in the BGO calorimeter and on their measured energies. We require

(i) at least two but no more than twelve shower peaks;

(ii) two of them should have an energy between 35 GeV and 55 GeV.

The first cut eliminates a major fraction of the hadronic events. The second one eliminates cosmic ray interactions, hadronic and $\tau\tau$ events.

(iii) Next, we eliminate all events in which both major shower peaks have a matching track in the vertex chamber within 50 mrad in transverse projection.

The result is a sample of 35 candidates with no matching vertex chamber tracks and a sample of 4 candidates with one matching vertex chamber track. Further examination of the latter sample indicates that only one of them is a recognizable γ conversion in the beam pipe with both decay tracks clearly separated. It should be noted that from the material in front of the TEC we expect 0.7 γ conversions in our sample. The remaining 3 events are classified as $e^+e^-\to e^+e^-$ events with one track detected and are eliminated from the sample. The contamination in the remaining sample where $e^+e^-\to e^+e^-$ with both tracks undetected is less than 0.005 events.

Fig. 1 shows a plot of $(E_1+E_2)/\sqrt{s}$ versus $\theta_1+\theta_2-\pi$ for the centers of the shower peaks of the remaining 36 events. The figure shows the presence of 4 events with $E_1+E_2<0.9\sqrt{s}$, which combine a relatively large acollinearity with a low total energy. Initial state radiation produces events of this type. It affects the angular distribution in eq. (1), therefore a cut is imposed requiring $E_1+E_2>0.9\sqrt{s}$. Applying the same cut to a Monte Carlo sample [of about 1000 $e^+e^-\to\gamma\gamma(\gamma)$ events] indicates that it has an acceptance of 89% in the polar angle region under consideration; the number of events removed by the cut agrees with this acceptance.

After the above cut we are left with a sample of 32 events.

4. Analysis $e^+e^-\to\gamma\gamma$

Table 1 presents the cross sections observed for $e^+e^-\to\gamma\gamma$ for three different center of mass energy regions and for the polar region under consideration.

Table 1

Region	Energy (GeV)	Luminosity (pb^{-1})	Events	Visible cross section
below Z	89.50	0.567	8	16.2 ± 5.4
on Z	91.28	1.202	18	17.2 ± 3.8
above Z	93.17	0.471	6	14.7 ± 5.6
all	91.22	2.240	32	16.4 ± 2.7

Within this angular range the efficiency of the electromagnetic calorimeter is $(98 \pm 1)\%$. Also given are the corresponding integrated luminosities and the number of events.

Integration of the lowest order QED differential cross section between $\frac{1}{4}\pi$ and $\frac{3}{4}\pi$ yields a prediction of 16.4 pb at 91.2 GeV. Applying the required radiative corrections, up to order α^3, using a program written by Berends and Kleiss [4] changes the QED-prediction to 16.8 pb, in agreement with the results presented in table 1.

Fig. 2 shows a comparison between the radiatively corrected QED angular dependence and our data points. The $\cos\theta$ dependence of the data is consistent with QED. To test the agreement with QED we used the binning-free Smirnov–Cramér–von Mises test

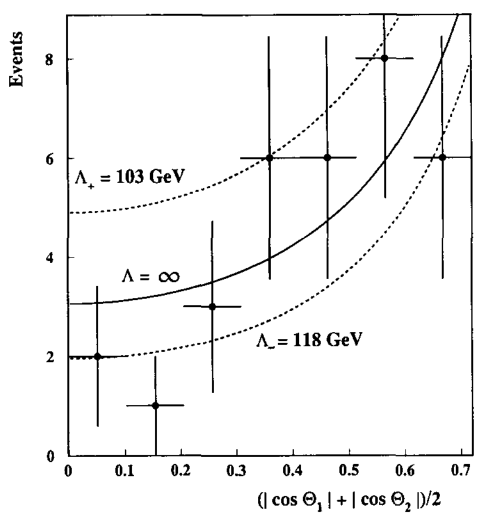

Fig. 2. The measured number of events versus $\frac{1}{2}(|\cos\theta_1| + |\cos\theta_2|)$. The solid curves show the QED prediction and the expectations with the cutoff parameters $\Lambda_+ = 103$ GeV and $\Lambda_- = 118$ GeV (95% confidence level limit).

Table 2

Experiment	Λ_+ (GeV)	Λ_- (GeV)
L3 (this experiment)	103	118
OPAL	82	89
CELLO	59	44
JADE	61	57
MARK J	72	65
PLUTO	46	–
TASSO	61	56
HRS	59	59
MAC	66	67
AMY	65	–
TOPAZ	94	59

[6]. Parametrizing a possible QED deviation as indicated in the introduction, and varying the cutoff Λ parameters, one obtains the following limits at the 95% confidence level:

$$\Lambda_+ > 103\ \text{GeV}, \quad \Lambda_- > 118\ \text{GeV}.$$

Table 2 shows a comparison between these limits and previously obtained e^+e^- results [7].

It is possible to parametrize a modification of the electron propagator in the reaction $e^+e^- \to \gamma\gamma$ in terms of the exchange of a virtual excited electron e^* [3]. The two parameters that enter into consideration then are λ, the ratio of the e^* to e coupling, and M_{e^*}, the mass of the e^*. Assuming $\lambda = 1$ we find at 95% CL

$$M_{e^*} > 83\ \text{GeV}.$$

This result is in agreement with limits recently obtained [8–10].

5. Rare Z^0 decays

Any deviation from the QED prediction for the

$e^+e^- \to \gamma\gamma$ cross section could also be due to rare Z^0 decays such as the theoretically forbidden $Z^0 \to \gamma\gamma$ [11] or the decays $Z^0 \to \pi^0\gamma$, $Z^0 \to \eta\gamma$, in which the π^0 or η would be indistinguishable from a γ. A difference between such Z^0 decays and QED events is the angular distribution. The QED reaction is strongly peaked forward whereas the Z^0 decays show essentially a $1+\cos^2\theta$ dependence. Upper limits for the Z^0 decays can thus be obtained by determining the amount of extra contribution of the type $1+\cos^2\theta$ our $\gamma\gamma$ sample is able to accommodate in the θ region under consideration. Taking into account the geometrical acceptances and the η-decay modes one arrives at detection efficiencies of 62%, 62% and 43% for $Z^0 \to \gamma\gamma$, $Z^0 \to \pi^0\gamma$ and $Z^0 \to \eta\gamma$ respectively. Using these numbers one derives [6] at 95% confidence level the following upper limits:

$$BR(Z^0 \to \gamma\gamma) < 2.9 \times 10^{-4} ,$$

$$BR(Z^0 \to \pi^0\gamma) < 2.9 \times 10^{-4} ,$$

$$BR(Z^0 \to \eta\gamma) < 4.1 \times 10^{-4} .$$

As an extension of the $e^+e^- \to \gamma\gamma$ study, a search was made for the higher order QED process $e^+e^- \to \gamma\gamma\gamma$. The selection criteria used were the following:

(i) at least three shower peaks, together having an energy greater than $0.5\sqrt{s}$;

(ii) an acoplanarity between these clusters of less than 9 degrees;

(iii) no matching tracks in the vertex chamber.

No candidate events are found. The acceptance of the above cuts, for the process $Z^0 \to \gamma\gamma\gamma$, roughly corresponds to the 3γ acceptance of the BGO barrel i.e. 35%. Using Poisson statistics we derive

$$BR(Z^0 \to \gamma\gamma\gamma) < 1.2 \times 10^{-4}$$

at the 95% confidence level.

The standard model predicts a $BR(Z^0 \to \gamma\gamma\gamma)$ of 8×10^{-10} [12]. However, in some composite models branching ratio's as high as 2×10^{-4} have been predicted [13].

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