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Measurement of the $e^+e^- \rightarrow Z\gamma\gamma$ Cross Section and Study of Anomalous Quartic Gauge Couplings

The L3 Collaboration

Abstract

The cross section of the process $e^+e^- \rightarrow Z\gamma\gamma \rightarrow q\bar{q}\gamma\gamma$ is measured using a total integrated luminosity of $0.5\,\mathrm{fb}^{-1}$ collected with the L3 detector at centre-of-mass energies between 130.1 GeV and 201.7 GeV. The results are consistent with the Standard Model expectations and limit the values of the possible anomalous Quartic Gauge Boson Couplings a_0/Λ^2 and a_c/Λ^2 as $-0.007\ \mathrm{GeV}^{-2} < a_0/\Lambda^2 < 0.005\ \mathrm{GeV}^{-2}$ and $-0.006\ \mathrm{GeV}^{-2} < a_c/\Lambda^2 < 0.011\ \mathrm{GeV}^{-2}$ at 95% confidence level.

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1 Introduction

The LEP centre-of-mass energy ($\sqrt{s}$) for e^+e^- collisions allows the production of three gauge bosons, through the processes $e^+e^- \rightarrow Z\gamma\gamma$ [1] and $e^+e^- \rightarrow W^+W^-\gamma$ [2]. The study of these processes gives a new insight into the Standard Model of electroweak interactions (SM) [3] and allows to probe quartic gauge boson couplings (QGC).

In the SM the $e^+e^- \rightarrow Z\gamma\gamma$ process occurs by radiation of the photons from the incoming electron and/or positron, corresponding to a total of six diagrams, three of which are presented in Figure 1. No QGC contribution is predicted at the tree level and $Z\gamma\gamma$ events are hence sensitive to anomalous QGC [4–6] effects, stemming from the last diagram shown in Figure 1.

The first measurement [1] of the cross section of the process $e^+e^- \rightarrow Z\gamma\gamma$, followed by the hadronic decay of the Z, was reported by the L3 Collaboration using data collected at LEP in 1997 and 1998 at average centre-of-mass energies of $\sqrt{s} = 182.7$ GeV and $\sqrt{s} = 188.7$ GeV, corresponding to integrated luminosities of $55\,\mathrm{pb}^{-1}$ and $176\,\mathrm{pb}^{-1}$, respectively. This study is extended here to the data collected with the L3 detector [7] in 1995, 1996, 1997 and 1999 at $\sqrt{s} =$ 130.1 GeV, 136.1 GeV, 161.3 GeV, 172.3 GeV, 191.6 GeV 195.6 GeV, 199.6 GeV and 201.7 GeV and amounting respectively to integrated luminosities of $6.1\,\mathrm{pb}^{-1}$, $5.9\,\mathrm{pb}^{-1}$, $10.9\,\mathrm{pb}^{-1}$, $10.2\,\mathrm{pb}^{-1}$, $29.4\,\mathrm{pb}^{-1}$, $83.7\,\mathrm{pb}^{-1}$, $82.8\,\mathrm{pb}^{-1}$, and $37.0\,\mathrm{pb}^{-1}$. Due to the relatively low luminosities collected at $\sqrt{s} = 130.1$ GeV and 136.1 GeV, these two data samples are interpreted as a single luminosity averaged one at $\sqrt{s} = 133.1$ GeV. Similar considerations lead to merge the $\sqrt{s} = 161.3$ GeV and 172.3 GeV samples into a $\sqrt{s} = 166.8$ GeV one.

The $e^+e^- \rightarrow Z\gamma\gamma \rightarrow q\bar{q}\gamma\gamma$ signal is defined here by three phase space cuts: photon energies above 5 GeV, photon angles with respect to the beam axis between 14° and 166° and invariant mass of the primary produced quarks within a $\pm 2\Gamma_Z$ window around the Z mass, Γ_Z being the Z width. Within these criteria, the KK2f Monte Carlo (MC) program [8] predicts signal cross sections between $0.31\,\mathrm{pb}^{-1}$and $0.9\,\mathrm{pb}^{-1}$, as listed in Table 1, where the error on the predictions is the quadratic sum of the MC statistical error and the theory uncertainty, estimated as suggested in Reference [8].

2 Event Selection

The selection of events satisfying the signal definition given above is optimised using hadronic events generated with the KK2f MC program. MC events failing the signal definition are termed QCD$\gamma\gamma$ background. Other background processes are generated with the MC programs PYTHIA 5.72 [9] ($e^+e^- \rightarrow Ze^+e^-$ and $e^+e^- \rightarrow ZZ$), KORALZ 4.02 [10] ($e^+e^- \rightarrow \tau^+\tau^-(\gamma)$), PHOJET 1.05c [11] ($e^+e^- \rightarrow e^+e^-q\bar{q}$) and KORALW 1.21 [12] for W^+W^- production except for the $e\nu_e q\bar{q}'$ final states which are generated with EXCALIBUR [13]. Additional background sources are negligible.

The L3 detector response is simulated using the GEANT 3.15 program [14], which takes into account the effects of energy loss, multiple scattering and showering in the detector. Time dependent detector inefficiencies, as measured in each data taking period, are reproduced in these simulations.

The selection of $e^+e^- \rightarrow Z\gamma\gamma \rightarrow q\bar{q}\gamma\gamma$ candidates from balanced hadronic events with two photons is based on photon energies and angles, together with the invariant mass and the boost of the hadronic system. It relies on criteria similar to those devised for the $\sqrt{s} = 182.7$ GeV and $\sqrt{s} = 188.7$ GeV data analyses [1], adapted to the different centre–of–mass energies.

3 Results

The application of the selection procedure yields the signal efficiencies and selected data and MC events summarised in Table 2. A clear signal structure at the Z mass is observed in the recoil mass spectra of the two photons, presented in Figure 2 for all the centre-of-mass energies under study and their combination together with those found by the $\sqrt{s} = 182.7$ GeV and $\sqrt{s} = 188.7$ GeV data analyses. The $\mathrm{e^+e^-} \rightarrow \mathrm{Z}\gamma\gamma \rightarrow \mathrm{q\bar{q}}\gamma\gamma$ cross sections are then determined from a fit to these spectra and are listed in Table 1.

The relative systematic uncertainties on the cross section measurements are evaluated to be of the order of 10% from the sources previously investigated [1]. The cross section results are in good agreement with these predictions. These results are also presented in Figure 3 together with the expected evolution with $\sqrt{s}$ of the SM cross section.

4 Limits on Quartic Gauge Boson Couplings

Anomalous QGC contributions to $\mathrm{Z}\gamma\gamma$ production via the s-channel exchange of a Z are described by two additional terms of dimension six in the Lagrangian [4]:

$$\mathcal{L}_6^0 = -\frac{\pi\alpha}{4\Lambda^2} a_0 F_{\mu\nu} F^{\mu\nu} \vec{W}_\rho \cdot \vec{W}^\rho \qquad \mathcal{L}_6^c = -\frac{\pi\alpha}{4\Lambda^2} a_c F_{\mu\rho} F^{\mu\sigma} \vec{W}^\rho \cdot \vec{W}_\sigma,$$

where α is the electromagnetic coupling, $F_{\mu\nu}$ is the field strength tensor of the photon and $\vec{W}_\mu$ is the weak boson field. The parameters a_0 and a_c describe the strength of the QGC and Λ represents the scale of the New Physics responsible for the coupling. $\mathcal{L}_6^0$ and $\mathcal{L}_6^c$ are separately C and P conserving and no CP violating operators contribute to the anomalous $\mathrm{ZZ}\gamma\gamma$ vertex.

QGC are expected to manifest themselves via deviations in the total $\mathrm{e^+e^-} \rightarrow \mathrm{Z}\gamma\gamma$ cross section [5], as presented in Figure 3. As the $\mathrm{Z}\gamma\gamma$ production occurs in the SM via t-channel diagrams, the three body phase space favoured in the QGC mediated production is different, in particular resulting in a harder spectrum of the least energetic photon [6]. Figure 4a compares the sum of the reconstructed spectra for all the investigated centre–of-mass energies, including the $\sqrt{s} = 182.7$ GeV and $\sqrt{s} = 188.7$ GeV results [1] with the predictions from signal and background MC. The expectations for an anomalous value of a_0/Λ^2 or a_c/Λ^2 are also shown. These QGC predictions are obtained by reweighting [1] each SM signal MC event with a factor [5] function of its phase space and the values of the couplings.

A simultaneous fit to the energy spectra for each centre–of-mass energy, including those at $\sqrt{s} = 182.7$ GeV and $\sqrt{s} = 188.7$ GeV, is performed, leaving one of the two QGC free at a time and fixing the other to zero. This yields the 68% confidence level (CL) measurements:

$$a_0/\Lambda^2 = 0.000 \pm 0.003\ \mathrm{GeV}^{-2} \ \text{ and } \ a_c/\Lambda^2 = 0.003 \pm 0.004\ \mathrm{GeV}^{-2}\,,$$

in agreement with the expected SM value of zero. A simultaneous fit to both the parameters allows to set the 95% CL limits:

$$-0.007\ \mathrm{GeV}^{-2} < a_0/\Lambda^2 < 0.005\ \mathrm{GeV}^{-2} \ \text{ and } \ -0.006\ \mathrm{GeV}^{-2} < a_c/\Lambda^2 < 0.011\ \mathrm{GeV}^{-2}\,,$$

also shown in Figure 4b. The experimental systematic uncertainties and those on the SM $\mathrm{e^+e^-} \rightarrow \mathrm{Z}\gamma\gamma \rightarrow \mathrm{q\bar{q}}\gamma\gamma$ cross section predictions are taken into account in the fit procedure.

References

[1] L3 Collab., M. Acciarri *et al.*, Phys. Lett. **B 478** (2000) 39.

[2] OPAL Collab., G. Abbiendi *et al.*, Phys. Lett. **B 471** (2000) 293.

[3] S. L. Glashow, Nucl. Phys. **22** (1961) 579; A. Salam, in Elementary Particle Theory, ed. N. Svartholm, (Almqvist and Wiksell, Stockholm, 1968), p. 367; S. Weinberg, Phys. Rev. Lett. **19** (1967) 1264.

[4] G. Bélanger and F. Boudjema, Phys. Lett. **B 288** (1992) 201.

[5] W. J. Stirling and A. Werthenbach, Eur. Phys. J **C 14** (2000) 103.

[6] G. Bélanger *et al.*, Eur. Phys. J **C 13** (2000) 283.

[7] L3 Collab., B. Adeva *et al.*, Nucl. Inst. Meth. **A 289** (1990) 35; L3 Collab., O. Adriani *et al.*, Physics Reports **236** (1993) 1; I. C. Brock *et al.*, Nucl. Instr. and Meth. **A 381** (1996) 236; M. Chemarin *et al.*, Nucl. Inst. Meth. **A 349** (1994) 345; M. Acciarri *et al.*, Nucl. Inst. Meth. **A 351** (1994) 300; A. Adam *et al.*, Nucl. Inst. Meth. **A 383** (1996) 342; G. Basti *et al.*, Nucl. Inst. Meth. **A 374** (1996) 293.

[8] S. Jadach, B.F.L. Ward and Z. Wąs, Preprint CERN-TH/99-235, hep-ph/9912214.

[9] T. Sjöstrand, CERN–TH/7112/93 (1993), revised August 1995; T. Sjöstrand, Comp. Phys. Comm. **82** (1994) 74.

[10] S. Jadach, B. F. L. Ward and Z. Wąs, Comp. Phys. Comm **79** (1994) 503.

[11] R. Engel, Z. Phys. **C 66** (1995) 203; R. Engel and J. Ranft, Phys. Rev. **D 54** (1996) 4244.

[12] M. Skrzypek *et al.*, Comp. Phys. Comm. **94** (1996) 216; M. Skrzypek *et al.*, Phys. Lett. **B 372** (1996) 289.

[13] R. Kleiss and R. Pittau, Comp. Phys. Comm. **85** (1995) 447; R. Pittau, Phys. Lett. **B 335** (1994) 490.

[14] The L3 detector simulation is based on GEANT Version 3.15. R. Brun *et al.*, "GEANT 3", CERN–DD/EE/84–1 (Revised), 1987. The GHEISHA program (H. Fesefeldt, RWTH Aachen Report PITHA 85/02 (1985)) is used to simulate hadronic interactions.

$\sqrt{s}$ (GeV)	$\sigma_{e^+e^- \to Z\gamma\gamma \to q\bar{q}\gamma\gamma}$ (pb)	$\sigma^{SM}_{e^+e^- \to Z\gamma\gamma \to q\bar{q}\gamma\gamma}$ (pb)
133.1	$0.8^{+0.5}_{-0.3} \pm 0.1$	0.962 ± 0.012
166.8	$0.22^{+0.20}_{-0.13} \pm 0.02$	0.496 ± 0.006
191.6	$0.12^{+0.16}_{-0.10} \pm 0.01$	0.350 ± 0.003
195.6	$0.29^{+0.11}_{-0.09} \pm 0.03$	0.333 ± 0.004
199.6	$0.24^{+0.10}_{-0.08} \pm 0.02$	0.313 ± 0.004
201.7	$0.47^{+0.20}_{-0.16} \pm 0.04$	0.311 ± 0.004

Table 1: Measured and expected cross sections for the process $e^+e^- \to Z\gamma\gamma \to q\bar{q}\gamma\gamma$. The first error of the measured values is statistical, the second systematic. The uncertainty on the prediction includes MC statistics and theory uncertainty.

$\sqrt{s}$ (GeV)	133.1	166.8	191.6	195.6	199.6	201.7
ε	0.41	0.52	0.41	0.45	0.43	0.47
Data	4	4	2	14	12	11
MC	5.6	6.5	5.5	16.8	14.4	6.8
$Z\gamma\gamma$	4.6	5.2	4.2	12.4	11.1	5.3
QCD$\gamma\gamma$	1.0	1.3	1.3	4.2	3.2	1.5
Other	< 0.1	< 0.1	< 0.1	0.2	0.1	< 0.1

Table 2: Yields of the $e^+e^- \to Z\gamma\gamma \to q\bar{q}\gamma\gamma$ selections. The signal efficiencies ε and the number of expected events for data and MC are given.

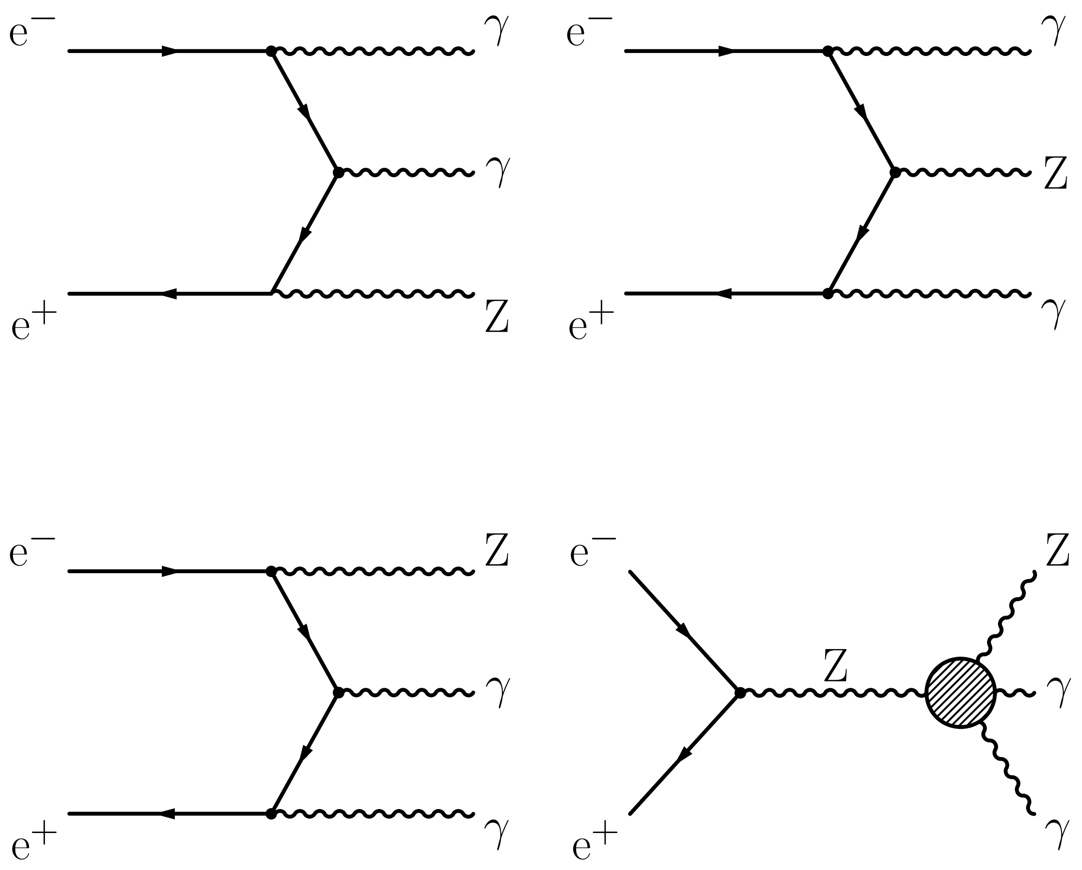


Figure 1: Three of the six SM diagrams contributing to $e^+e^- \rightarrow Z\gamma\gamma$ production. The other three SM diagrams are obtained by crossing the photon lines. A possible anomalous QGC diagram is also shown.

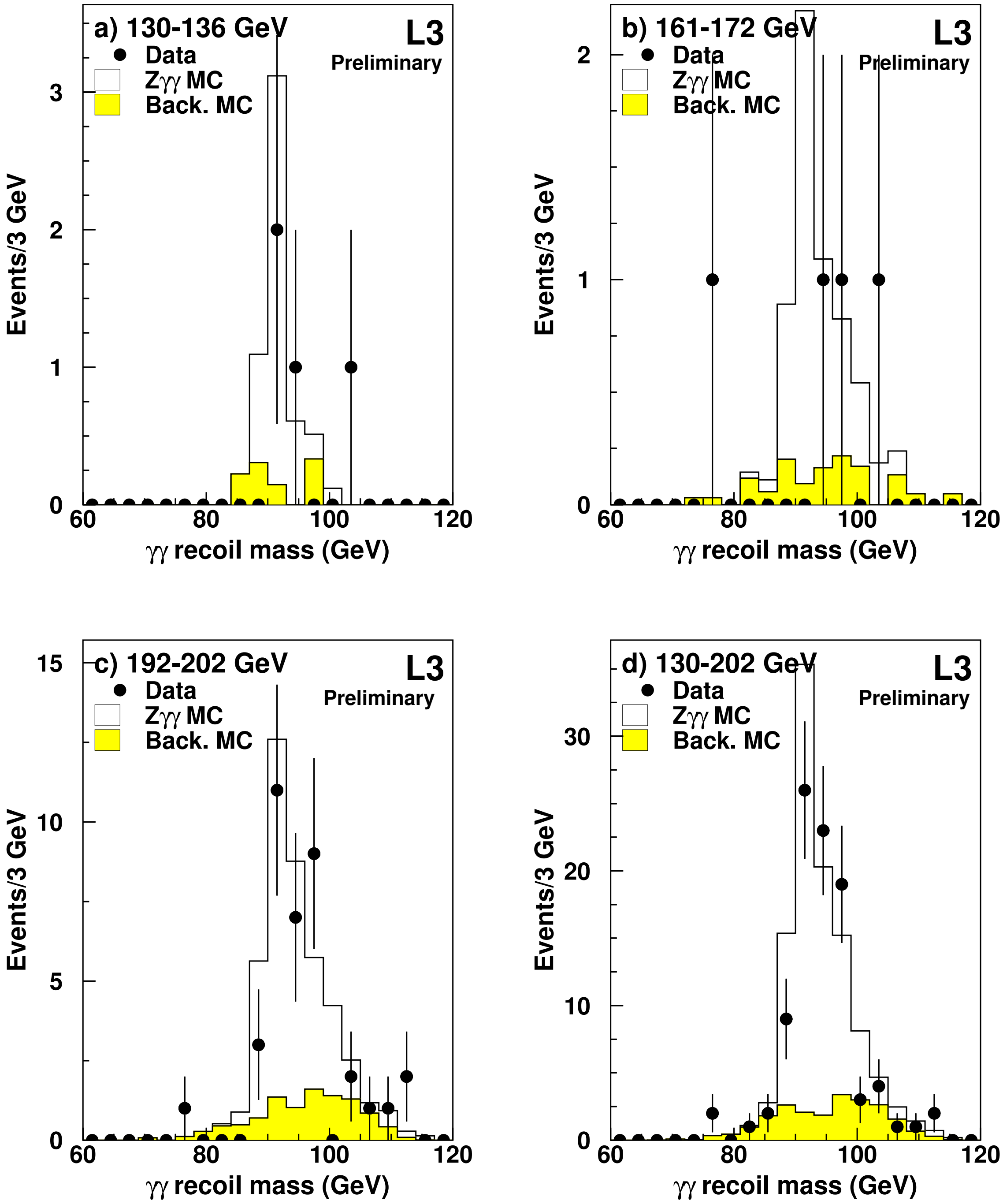


Figure 2: Recoil mass to the photon pairs at (a) $\sqrt{s}$ = 130.1 − 136.1 GeV, (b) $\sqrt{s}$ = 161.3 − 172.3 GeV, (c) $\sqrt{s}$ = 191.6 − 201.7 GeV in data, $Z\gamma\gamma \rightarrow q\bar{q}\gamma\gamma$ and background MC. (d) presents their combination with the $\sqrt{s}$ = 182.7 GeV and 188.7 GeV results.

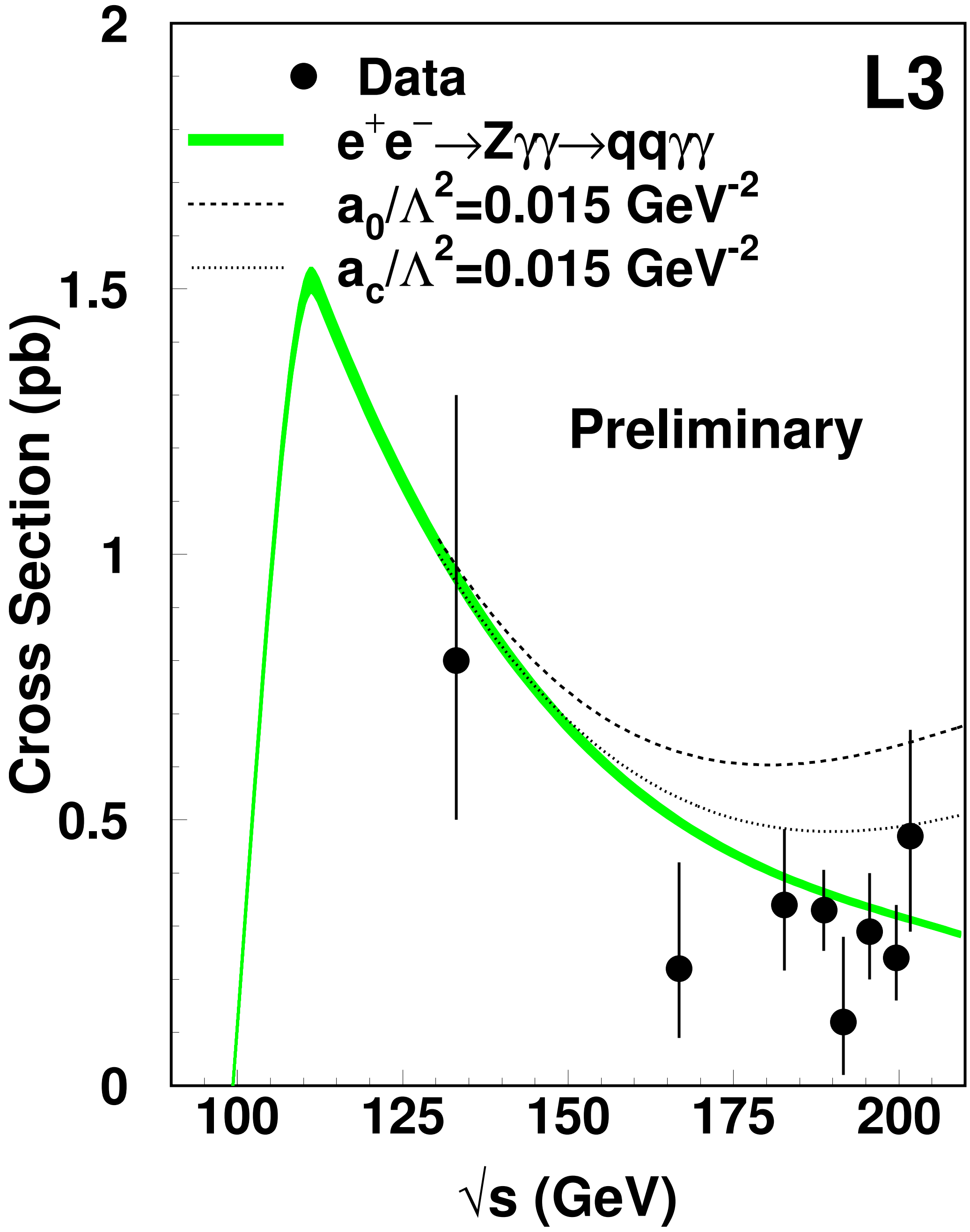
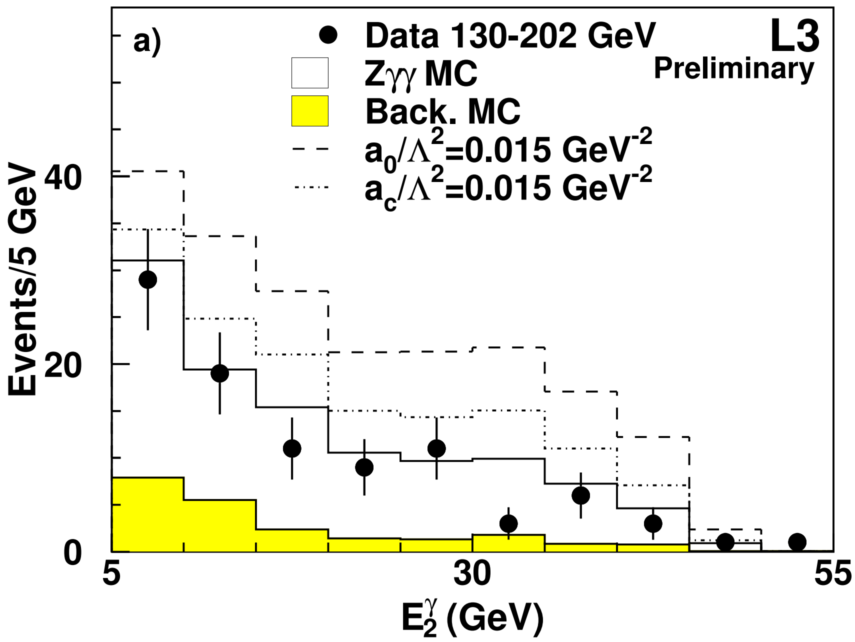


Figure 3: Evolution of the $e^+e^- \rightarrow Z\gamma\gamma \rightarrow q\bar{q}\gamma\gamma$ cross section with the centre-of-mass energy. Signal definition cuts described in the text are applied. The width of the band corresponds to the error that arises from MC statistics and theory uncertainty, estimated to be 1.5%. Dashed and dotted lines represent QGC predictions.



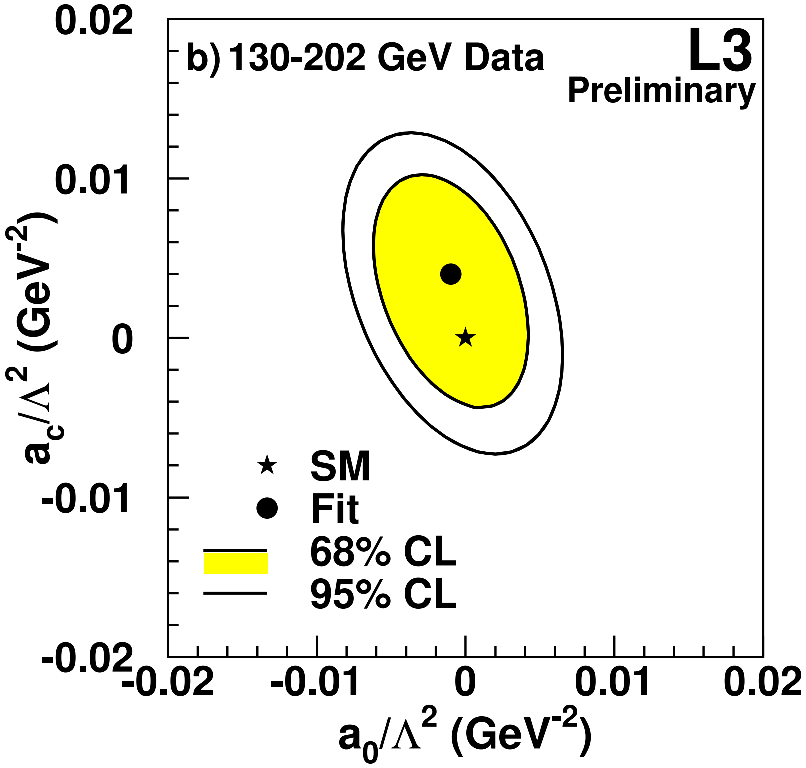


Figure 4: a) Energy E_2^γ of the least energetic photon for the full data sample. Data, $Z\gamma\gamma \to q\bar{q}\gamma\gamma$ and background MC are displayed together with anomalous QGC predictions. b) Two dimensional contours for the QGC parameters a_0/Λ^2 and a_c/Λ^2.