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Hard-Photon Production and Tests of QED at LEP

The L3 Collaboration

Abstract

The total and differential cross sections of the process $e^+e^- \rightarrow n\gamma$ with $n \geq 2$ are measured using data collected by the L3 experiment at centre–of–mass energies of $\sqrt{s} = 183$ and 189 GeV. The results are in agreement with the Standard Model expectations. Limits are set on deviations from QED, contact interaction cut-off parameters and masses of excited electrons.

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1 Introduction

The process $\mathrm{e^+e^-} \rightarrow \gamma\gamma(\gamma)$, where (γ) denotes possible additional photons, is described very accurately by QED. The experimental signature of these events is clean, and they can be selected with negligible background. Therefore, this process is well suited to test QED and to look for new physics phenomena, whose expected contributions grow with the increase of the centre–of–mass energy, $\sqrt{s}$.

In this paper, the results on the study of the process $\mathrm{e^+e^-} \rightarrow n\gamma$ ($n \geq 2$) are presented. The analysis is performed on the data sample collected by the L3 detector [1] during 1997 and 1998, at $\sqrt{s} = 182.7$ GeV (183 GeV hereafter) and $\sqrt{s} = 188.7$ GeV (189 GeV hereafter) respectively. The integrated luminosities for each sample are 54.8 $\mathrm{pb^{-1}}$ and 175.3 $\mathrm{pb^{-1}}$, respectively. Previous results have been published by L3 at lower centre-of-mass energies [2–4] and by other experiments [5].

2 Event selection

The analysis performed on these data is similar to that reported in previous papers [4]. A photon candidate is defined as:

- A shower in the electromagnetic barrel or end-cap calorimeters with energy larger than 1 GeV. The profile of the shower must be consistent with that of an electromagnetic particle.
- The number of hits in the vertex chamber within an azimuthal angle of $\pm 8^\circ$ around the direction of the photon candidate must be less than 40% of the expected number of hits for a charged particle.

To select an event there must be at least two photon candidates with polar angles θ_γ between 16° and 164° with an angular separation of more than 15° and no other activity in the detector. In addition, to reject $\mathrm{e^+e^-} \rightarrow \nu\bar{\nu}\gamma\gamma$ and cosmic rays, we require that the sum of the energies of the photon candidates be larger than $\sqrt{s}/2$.

The only expected backgrounds are $\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}(\gamma)$ and $\mathrm{e^+e^-} \rightarrow \tau^+\tau^-(\gamma)$. These contributions are estimated from Monte Carlo simulations using BHWIDE [6] for Bhabha events and KORALZ [7] for τ events, and are found to be negligible. The acceptance is computed applying the same analysis to a sample of $\mathrm{e^+e^-} \rightarrow \gamma\gamma(\gamma)$ events generated using an order α^3 Monte Carlo generator [8] passed through the L3 simulation [9] and reconstruction programs. The selection efficiencies to detect at least two photons inside the fiducial volume are found to be $68.8 \pm 0.2\%$ at $\sqrt{s} = 183$ GeV and $68.0 \pm 0.2\%$ at $\sqrt{s} = 189$ GeV for $16^\circ < \theta_\gamma < 164^\circ$, where the errors quoted are the statistical errors of the Monte Carlo sample. The efficiency of the calorimetric energy trigger is estimated to be above 99.7 % for both samples. It is estimated by using a sample of Bhabha events, which has an independent trigger for charged particles.

3 Analysis

A total of 460 events at $\sqrt{s} = 183$ GeV and 1374 events at $\sqrt{s} = 189$ GeV are selected. They are classified according to the number of isolated photons in $16^\circ < \theta_\gamma < 164^\circ$, as presented in Table 1, together with the number of expected events. Figure 1 shows one event with 4 detected photons at $\sqrt{s} = 183$ GeV. No events with 5 or more photons in this angular range have been observed. For the two most energetic photons, the acollinearity angle distribution is shown in Figure 2, and the acoplanarity angle distribution in Figure 3.

	$\sqrt{s} = 183$ GeV		$\sqrt{s} = 189$ GeV	
	N_{obs}	N_{exp}	N_{obs}	N_{exp}
2γ	436	453	1302	1346
3γ	23	24	72	69
4γ	1	0.04	0	0.1

Table 1: Number of observed, N_{obs}, and expected, N_{exp}, events with 2, 3 and 4 photons.

The differential cross section as a function of the $\cos\theta$ of the event is shown in Figure 4. The polar angle θ of the event is defined as $\cos\theta = |\sin(\frac{\theta_1-\theta_2}{2})/\sin(\frac{\theta_1+\theta_2}{2})|$, where θ_1 and θ_2 are the polar angles of the two most energetic photons in the event. The measured differential distributions have been corrected for efficiency and higher order QED contributions using the Monte Carlo simulation. These distributions are then compared directly with the lowest order QED predictions. Good agreement between the data and the QED prediction is observed.

The observed number of events corresponds to a total cross section in the fiducial region $16^\circ < \theta < 164^\circ$ of:

$$\begin{aligned} \sigma_{\gamma\gamma(\gamma)} &= 12.17 \pm 0.55 \pm 0.14 \text{ pb} \quad (\sqrt{s} = 183 \text{ GeV}) \\ \sigma_{\gamma\gamma(\gamma)} &= 11.54 \pm 0.30 \pm 0.14 \text{ pb} \quad (\sqrt{s} = 189 \text{ GeV}), \end{aligned}$$

where the first error is statistical and the second is systematic. The main source of systematic error is the uncertainty in the selection efficiency. It has been evaluated by varying the selection cuts and taking into account the finite Monte Carlo statistics. The systematic error coming from the uncertainty in the measured luminosity ($\pm 0.2\%$) and in the background present in the sample ($< 0.5\%$) are found to be negligible. The statistical error dominates in the measurement of the cross section both at 183 GeV and at 189 GeV. The QED predicted cross sections are 12.65 pb and 11.78 pb [8] respectively, in agreement with the measurements.

These cross sections and previously measured values [2–4] together with the QED prediction, are presented in Figure 5 as a function of the centre-of-mass energy.

4 Limits on deviations from QED

The possible deviations from QED are parametrised by effective Lagrangians, and their effect on the observables can be expressed as a multiplicative correction term to the QED differential cross section. Depending on the type of Lagrangian, two general forms are considered [10]:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{QED}} \left(1 + \frac{s^2}{\alpha}\frac{1}{\Lambda^4}\sin^2\theta\right) \tag{1}$$

and

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm QED} \left(1 + \frac{s^3}{32\pi\alpha^2}\frac{1}{\Lambda'^6}\frac{\sin^2\theta}{1+\cos^2\theta}\right). \tag{2}$$

The correction factors depend on the centre-of-mass energy, the polar angle and the scale parameters Λ, Λ' which have dimensions of energy. A more standard way of parametrising the deviations from QED is the introduction of the cut-off parameters $\Lambda_\pm$ [11]. The differential cross section can be obtained from equation (1) by replacing Λ^4 by $\pm(2/\alpha)\Lambda_\pm^4$.

Limits on the different scale parameters have already been set in our previous publications [3, 4]. However, since the sensitivity to possible deviations from QED increases rapidly with the centre-of-mass energy they are superseded by the present data. In order to quantify the possible deviations from QED we perform a maximum likelihood fit to the differential cross sections at each centre-of-mass energy. The estimated parameters combining the present results with those in our previous analyses [3, 4] are:

$$\begin{aligned}\frac{1}{\Lambda^4} &= \left(-0.019^{+\,0.054}_{-\,0.038}\right) \times 10^{-11} \quad \mathrm{GeV}^{-4}\\ \frac{1}{\Lambda'^6} &= \left(-0.048^{+\,0.131}_{-\,0.092}\right) \times 10^{-16} \quad \mathrm{GeV}^{-6}\end{aligned}$$

consistent with no deviations from QED. To determine the confidence levels, the probability distribution is normalised over the physically allowed range of the parameters. At the 95% C.L. the following limits are obtained:

$$\begin{aligned}\Lambda &> 1304 \text{ GeV}, \quad \Lambda_+ > 321 \text{ GeV}\\ \Lambda' &> 703 \text{ GeV}, \quad \Lambda_- > 282 \text{ GeV}\end{aligned}$$

The effects of $\Lambda_\pm$ in the differential cross section can be seen in Figure 4. In this case, the parameters $\Lambda_\pm$ have been fixed to the limits values quoted before.

The existence of excited electrons (e^*) would also introduce deviations from the QED predictions in the $\gamma\gamma(\gamma)$ final states. The excited electron, of mass m_{e^*}, couples to e and γ via two possible interactions. The first is purely magnetic [12],

$$\mathcal{L} = \frac{e}{2\Lambda_{e^*}} \overline{\Psi}_{e^*}\sigma^{\mu\nu}\Psi_e F_{\mu\nu} + h.c.$$

and the second is a chiral-magnetic one [13]:

$$\mathcal{L} = \frac{e}{2\Lambda_{e^*}} \overline{\Psi}_{e^*}\sigma^{\mu\nu}(1\pm\gamma^5)\Psi_e F_{\mu\nu} + h.c.$$

In both cases we fit the excited electron mass fixing the interaction scale Λ_{e^*} to m_{e^*}, obtaining

$$\begin{aligned}\text{Purely Magnetic:} \quad \frac{1}{m_{e^*}^4} &= \left(-0.052^{+\,0.143}_{-\,0.104}\right) \times 10^{-9} \text{ GeV}^{-4}\\ \text{Chiral-Magnetic:} \quad \frac{1}{m_{e^*}^4} &= \left(-0.135^{+\,0.383}_{-\,0.352}\right) \times 10^{-9} \text{ GeV}^{-4}\end{aligned}$$

From them we derive the 95% C.L. lower limits of:

$$\begin{aligned}\text{Purely Magnetic:} \quad m_{e^*} &> 283 \text{ GeV}\\ \text{Chiral-Magnetic:} \quad m_{e^*} &> 213 \text{ GeV}\end{aligned}$$

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References

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

[2] L3 Collaboration, M. Acciarri *et al.*, Phys. Lett. **B 353** (1995) 136.

[3] L3 Collaboration, M. Acciarri *et al.*, Phys. Lett. **B 384** (1996) 323.

[4] L3 Collaboration, M. Acciarri *et al.*, Phys. Lett. **B 413** (1997) 159.

[5] ALEPH Collaboration, D. Buskulic *et al.*, Phys. Lett. **B 429** (1998) 201.
DELPHI Collaboration, P. Abreu *et al.*, Phys. Lett. **B 433** (1998) 429.
OPAL Collaboration, K. Ackerstaff *et al.*, Phys. Lett. **B 465** (1999) 303.

[6] S. Jadach *et al.*, Phys. Lett. **B 390** (1997) 298.

[7] S. Jadach *et al.*, Comp. Phys. Comm. **79** (1994) 503.

[8] F. A. Berends and R. Kleiss, Nucl. Phys.**B 186** (1981) 22;
CALKUL Collaboration, F. A. Berends *et al.*, Nucl. Phys. **B 239** (1984) 395.

[9] The L3 detector simulation is based on GEANT Version 3.15,
R. Brun *et al.*, 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.

[10] O. J. P. Eboli *et al.*, Phys. Lett. **B 271** (1991) 274.

[11] F.E. Low, Phys. Rev. Lett. **14** (1965) 238;
R. P. Feynman, Phys. Rev. Lett. **74** (1948) 939;
F. M. Renard, Phys. Lett. **B 116** (1982) 264;
S. Drell, Ann. Phys. (N.Y.) **4** (1958) 75.

[12] A. Litke, Harvard Univ., Ph.D Thesis (1970) unpublished.

[13] K. Hagiwara, S. Komamyia and D. Zeppenfeld, Z. Phys. **C 29** (1985) 115;
N. Cabibbo, L. Maiani and Y. Srivastava, Phys. Lett **B 139** (1984) 459;
F.M. Renard, Nucl. Phys. **B 196** (1982) 93.

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Holzner,[47] H.Hoorani,[33] S.R.Hou,[49] I.Iashvili,[46] B.N.Jin,[7] L.W.Jones,[3] P.de Jong,[2] I.Josa-Mutuberría,[25] R.A.Khan,[18] M.Kaur,[18,◇] M.N.Kienzle-Focacci,[19] D.Kim,[35] D.H.Kim,[41] J.K.Kim,[41] S.C.Kim,[41] J.Kirkby,[17] D.Kiss,[13] W.Kittel,[30] A.Klimentov,[14,27] A.C.König,[30] A.Kopp,[46] V.Koutsenko,[14,27] M.Kräber,[47] R.W.Kraemer,[33] W.Krenz,[1] A.Krüger,[46] A.Kunin,[14,27] P.Ladron de Guevara,[25] I.Laktineh,[24] G.Landi,[16] K.Lassila-Perini,[47] M.Lebeau,[17] A.Lebedev,[14] P.Lebrun,[24] P.Lecomte,[47] P.Lecoq,[17] P.Le Coultre,[47] H.J.Lee,[8] J.M.Le Goff,[17] R.Leiste,[46] E.Leonardi,[35] P.Levtchenko,[36] C.Li,[20] S.Likhoded,[46] C.H.Lin,[49] W.T.Lin,[49] F.L.Linde,[2] L.Lista,[28] Z.A.Liu,[7] W.Lohmann,[46] E.Longo,[35] Y.S.Lu,[7] K.Lübelsmeyer,[1] C.Luci,[17,35] D.Luckey,[14] L.Lugnier,[24] L.Luminari,[35] W.Lustermann,[47] W.G.Ma,[20] M.Maity,[10] L.Malgeri,[17] A.Malinin,[17] C.Maña,[25] D.Mangeol,[30] P.Marchesini,[47] G.Marian,[15] J.P.Martin,[24] F.Marzano,[35] G.G.G.Massaro,[2] K.Mazumdar,[10] R.R.McNeil,[6] S.Mele,[17] L.Merola,[28] M.Meschini,[16] W.J.Metzger,[30] M.von der Mey,[1] A.Mihul,[12] H.Milcent,[17] G.Mirabelli,[35] J.Mnich,[17] G.B.Mohanty,[10] P.Molnar,[8] B.Monteleoni,[16,†] T.Moulik,[10] G.S.Muanza,[24] F.Muheim,[19] A.J.M.Muijs,[2] M.Musy,[35] M.Napolitano,[28] F.Nessi-Tedaldi,[47] H.Newman,[31] T.Niessen,[1] A.Nisati,[35] H.Nowak,[46] Y.D.Oh,[41] G.Organtini,[35] A.Oulianov,[27] C.Palomares,[25] D.Pandoulas,[1] S.Paoletti,[35,17] P.Paolucci,[28] R.Paramatti,[35] H.K.Park,[33] I.H.Park,[41] G.Pascale,[35] G.Passaleva,[17] S.Patricelli,[28] T.Paul,[11] M.Pauluzzi,[32] C.Paus,[17] F.Pauss,[47] M.Pedace,[35] S.Pensotti,[26] D.Perret-Gallix,[4] B.Petersen,[30] D.Piccolo,[28] F.Pierella,[9] M.Pieri,[16] P.A.Piroué,[34] E.Pistolesi,[26] V.Plyaskin,[27] M.Pohl,[19] V.Pojidaev,[27,16] H.Postema,[14] J.Pothier,[17] N.Produit,[19] D.O.Prokofiev,[44] D.Prokofiev,[36] J.Quartieri,[37] G.Rahal-Callot,[47,17] M.A.Rahaman,[10] P.Raics,[15] N.Raja,[10] R.Ramelli,[47] P.G.Rancoita,[26] A.Raspereza,[46] G.Raven,[38] P.Razis,[29] D.Ren,[47] M.Rescigno,[35] S.Reucroft,[11] T.van Rhee,[43] S.Riemann,[46] K.Riles,[3] A.Robohm,[47] J.Rodin,[42] B.P.Roe,[3] L.Romero,[25] A.Rosca,[8] S.Rosier-Lees,[4] J.A.Rubio,[17] D.Ruschmeier,[8] H.Rykaczewski,[47] S.Saremi,[6] S.Sarkar,[35] J.Salicio,[17] E.Sanchez,[17] M.P.Sanders,[30] M.E.Sarakinos,[21] C.Schäfer,[17] V.Schegelsky,[36] S.Schmidt-Kaerst,[1] D.Schmitz,[1] H.Schopper,[48] D.J.Schotanus,[30] G.Schwering,[1] C.Sciacca,[28] D.Sciarrino,[19] A.Seganti,[9] L.Servoli,[32] S.Shevchenko,[31] N.Shivarov,[40] V.Shoutko,[27] E.Shumilov,[27] A.Shvorob,[31] T.Siedenburg,[1] D.Son,[41] B.Smith,[33] P.Spillantini,[16] M.Steuer,[14] D.P.Stickland,[34] A.Stone,[6] H.Stone,[34,†] B.Stoyanov,[40] A.Straessner,[1] K.Sudhakar,[10] G.Sultanov,[18] L.Z.Sun,[20] H.Suter,[47] J.D.Swain,[18] Z.Szillasi,[42,¶] T.Sztaricskai,[42,¶] X.W.Tang,[7] L.Tauscher,[5] L.Taylor,[11] C.Timmermans,[30] Samuel C.C.Ting,[14] S.M.Ting,[14] S.C.Tonwar,[10] J.Tóth,[13] C.Tully,[17] K.L.Tung,[7] Y.Uchida,[14] J.Ulbricht,[47] E.Valente,[35] G.Vesztergombi,[13] I.Vetlitsky,[27] D.Vicinanza,[37] G.Viertel,[47] S.Villa,[11] M.Vivargent,[4] S.Vlachos,[5] I.Vodopianov,[36] H.Vogel,[33] H.Vogt,[46] I.Vorobiev,[27] A.A.Vorobyov,[36] A.Vorvolakos,[29] M.Wadhwa,[5] W.Wallraff,[1] M.Wang,[14] X.L.Wang,[20] Z.M.Wang,[20] A.Weber,[1] M.Weber,[1] P.Wienemann,[1] H.Wilkens,[30] S.X.Wu,[14] S.Wynhoff,[17] L.Xia,[31] Z.Z.Xu,[20] B.Z.Yang,[20] C.G.Yang,[7] H.J.Yang,[7] M.Yang,[7] J.B.Ye,[20] S.C.Yeh,[50] An.Zalite,[36] Yu.Zalite,[36] Z.P.Zhang,[20] G.Y.Zhu,[7] R.Y.Zhu,[31] A.Zichichi,[9,17,18] G.Zilizi,[42,¶] M.Zöller.[1]

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† Deceased.

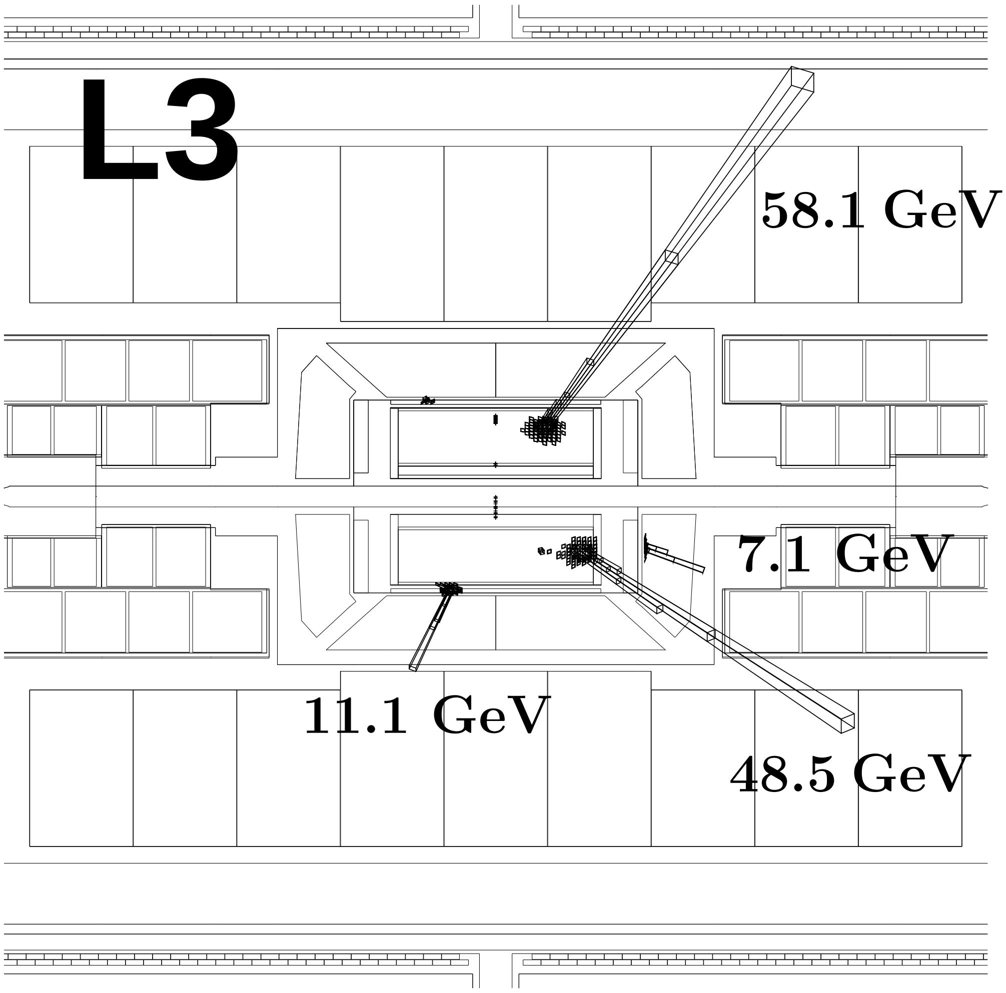


Figure 1: Display of an event with four detected photons at $\sqrt{s} = 183$ GeV.

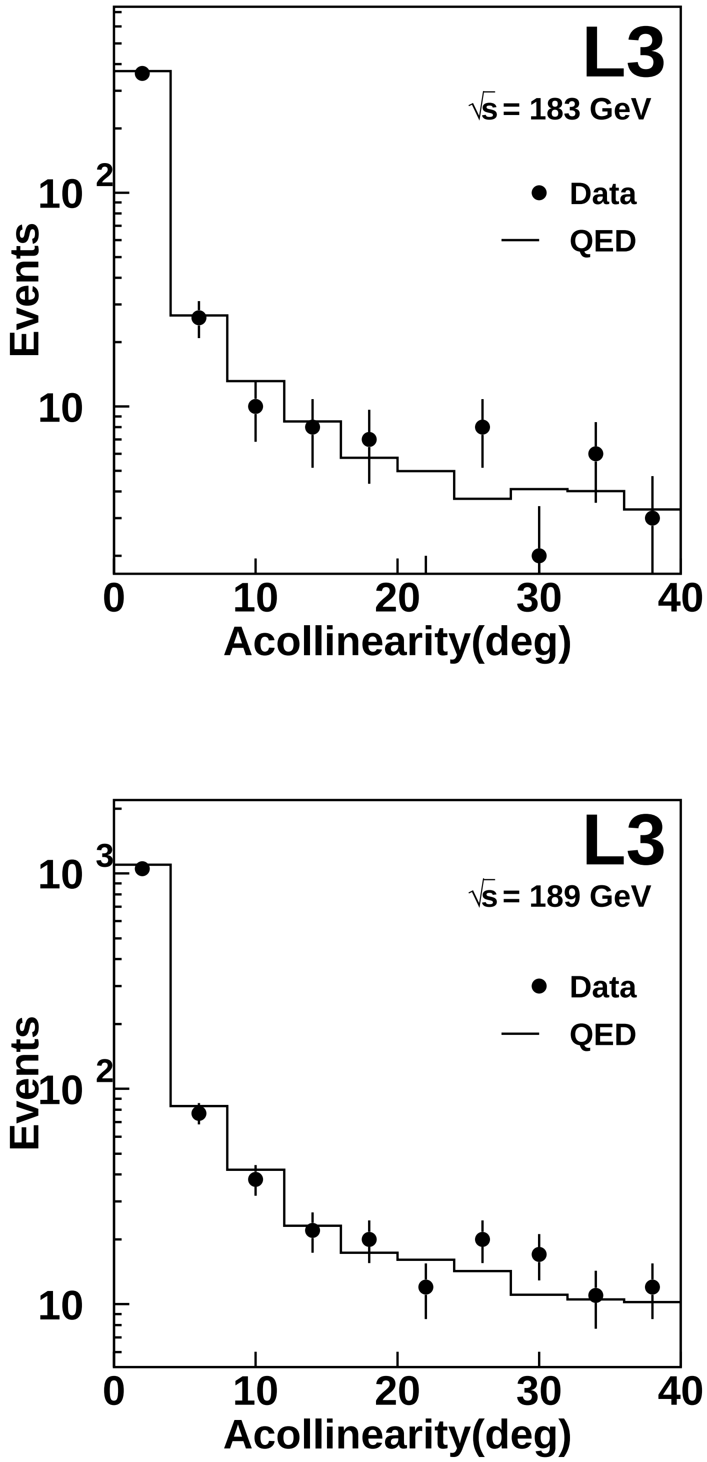


Figure 2: Distribution of the acollinearity angle between the two most energetic photons in the $e^+e^- \to \gamma\gamma(\gamma)$ process at $\sqrt{s} = 183$ GeV (top), and $\sqrt{s} = 189$ GeV (bottom).

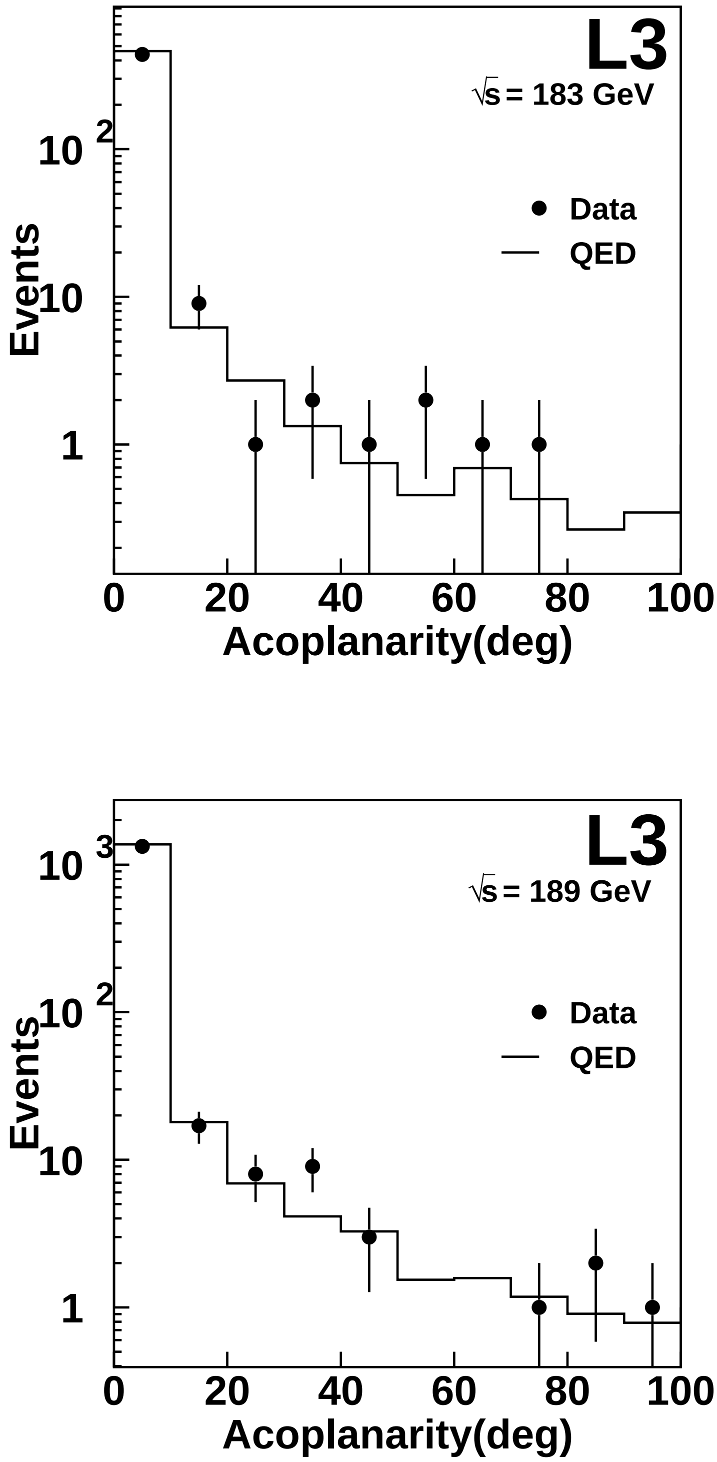
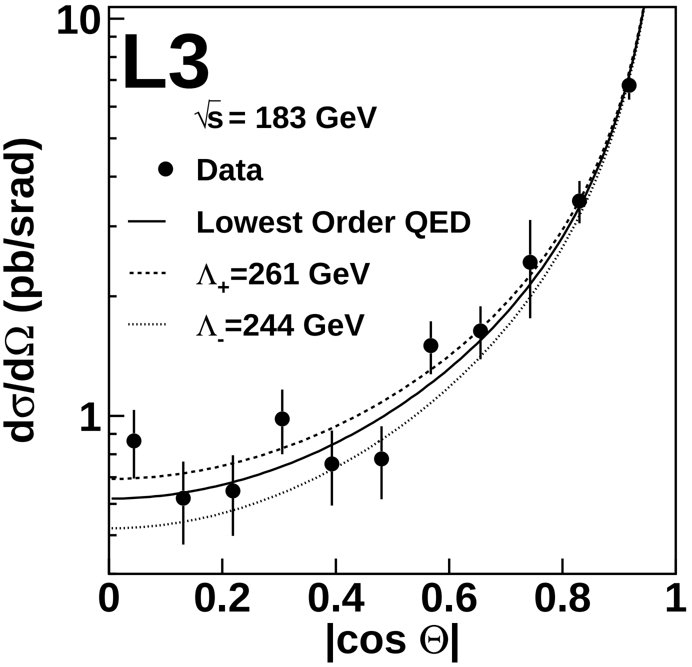


Figure 3: Distribution of the acoplanarity angle between the two most energetic photons in the $e^+e^- \rightarrow \gamma\gamma(\gamma)$ process at $\sqrt{s} = 183$ GeV (top), and $\sqrt{s} = 189$ GeV (bottom).



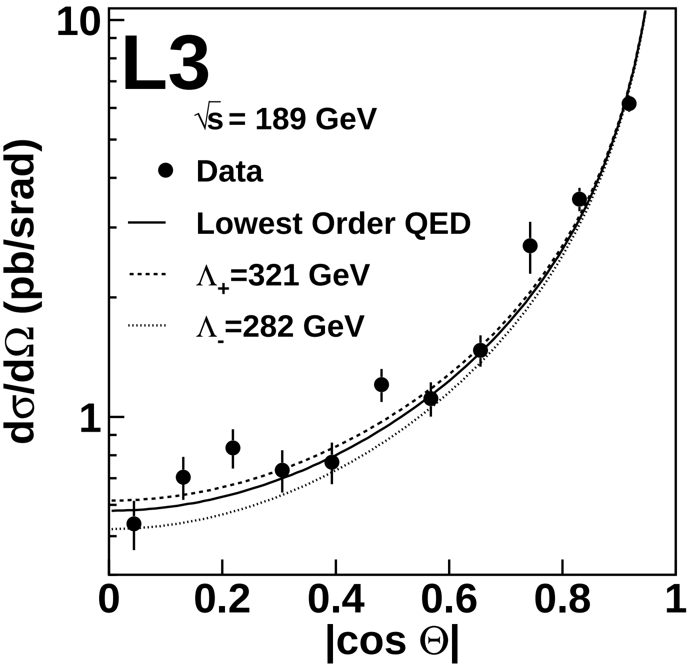


Figure 4: Differential cross section as a function of $\cos\theta$ for the process $e^+e^- \rightarrow \gamma\gamma(\gamma)$. The points show the measurements corrected for efficiency and additional photons. The solid line corresponds to the lowest order QED prediction. The dashed and dotted lines represent the limits obtained for deviations from QED, taking into account all the L3 data at centre-of-mass energies up to that presented in the corresponding plot.

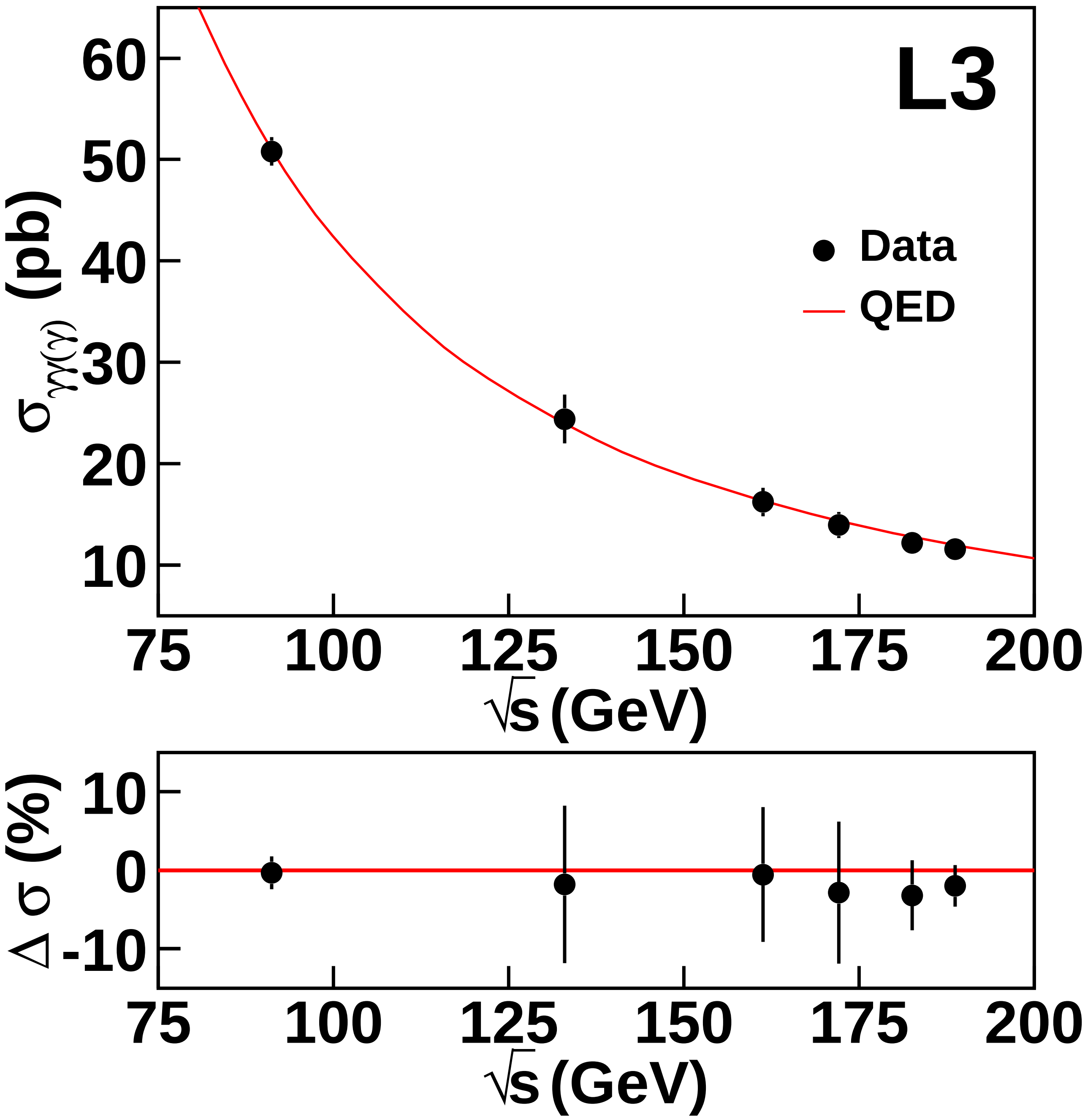


Figure 5: Measured cross section as a function of the centre-of-mass energy for θ between 16° and 164° compared with the QED prediction. The value at $\sqrt{s}$ = 91 GeV has been extrapolated to this angular range from the one given in [2]. The bottom part of the figure presents the relative deviation of the measurements with respect to the QED expectations.