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# Hard-photon production at $\sqrt{s} = 161$ and 172 GeV at LEP

The L3 Collaboration

## Abstract

We have studied the process $e^+e^- \to n\gamma$ ($n \geq 2$) at centre-of-mass energies of 161.3 GeV and 172.1 GeV. The analysis is based on a sample of events collected by the L3 detector in 1996 corresponding to total integrated luminosities of 10.7 pb$^{-1}$ and 10.1 pb$^{-1}$ respectively. The observed rates of events with two and more photons and the characteristic distributions are in good agreement with the Standard Model expectations. This is used to set lower limits on contact interaction energy scale parameters, on the QED cut-off parameters and on the mass of excited electrons.

# 1 Introduction

During 1996 LEP increased the centre-of-mass energy above 160 GeV providing a unique opportunity to search for new physics beyond the Standard Model. The process $e^+e^-\rightarrow$n$\gamma$ (n$\geq$2) is well suited for this purpose. On one hand it is a clean process with negligible background and with small non-QED radiative corrections. On the other hand it may be influenced by new phenomena, like compositeness or effective contact interactions, and its sensitivity increases with the centre-of-mass energy.

In this paper we present the results on the search for new physics based on the process $e^+e^-\rightarrow$n$\gamma$ (n$\geq$2). The analysis is performed with a sample of events collected by the L3 experiment in 1996 which corresponds to a total integrated luminosity of 10.69 pb$^{-1}$ at the centre-of-mass energy of 161.3 GeV and 10.09 pb$^{-1}$ at 172.1 GeV. Previous results have been published at lower centre-of-mass energies [1–3].

The L3 detector and its performance is described in detail in [4]. In 1996 a lead scintillator fibre calorimeter [5] was installed in the gap between the electromagnetic calorimeter barrel region and the end-caps to measure more precisely the energy of the particles which go into this region.

# 2 Event Selection

To obtain a clean sample of $e^+e^-\rightarrow$n$\gamma$ (n$\geq$2) events different selection criteria are applied. They are based on "photon candidates" defined as:

i) A shower in the electromagnetic calorimeter with a profile consistent with that of a photon and an energy above 1 GeV or a shower in the lead scintillator fibre calorimeter with an energy above 10 GeV which matches with a scintillator signal in time within a cone of 14° half-opening angle;

ii) The number of signals in the vertex chamber within a cone of 8° half-oppening azimuthal angle along the path of any photon candidate must be less than 40% of that expected for a charged particle.

To ensure a good identification a fiducial cut is applied requiring that the events have:

- At least two photon candidates with a polar angle $\theta_\gamma$ between 16° and 164° and an angular separation of more than 15°.

The main sources of background come from $e^+e^-\rightarrow\nu\overline{\nu}\gamma\gamma$ and cosmic rays. To reduce their contribution we require that:

- The sum of the energies of the photon candidates must be larger than $\sqrt{s}/2$.

With these selection cuts the contamination from other processes, estimated from Monte Carlo simulations, is negligible. In order to determine the acceptance, the same analysis is applied to a sample of $e^+e^-\rightarrow\gamma\gamma(\gamma)$ Monte Carlo generated events passed through the L3 simulation and reconstruction programs. The overall selection efficiency is found to be 79.3$\pm$0.2% for $\theta_\gamma$ between 16° and 164° and the trigger efficiency is estimated to be above 99.7%.

# 3 Analysis of $e^+e^-\to n\gamma$ ($n\geq 2$) events

After applying these selection cuts the number of observed events, classified according to the number of isolated photons within the range $16^\circ < \theta_\gamma < 164^\circ$, is given in Table 1 together with the number of expected events from the process $e^+e^-\to n\gamma$ (n = 2, 3, 4) for the two different centre-of-mass energies [6]. No events with 5 or more photons have been observed.

For the two most energetic photons of the $n\geq 2\,\gamma$ events the distribution of the acollinearity is shown in Figure 1 and of the invariant mass in Figure 2 together with the Monte Carlo expected distributions.

| | $\sqrt{s} = 161.3$ GeV | | $\sqrt{s} = 172.1$ GeV | |
|---|---|---|---|---|
| | Observed | Expected | Observed | Expected |
| $2\gamma$ | 131 | 130.6 | 109 | 108.7 |
| $3\gamma$ | 6 | 7.9 | 3 | 5.8 |
| $4\gamma$ | 0 | 0.3 | 2 | 0.2 |

Table 1: Observed and expected number of events with 2, 3 and 4 photons.

The distribution of the $\cos\theta^*$ of the event [1)] is shown in Figure 3 compared with the Monte Carlo prediction. The data shows good agreement with QED.

The 137 and 112 observed events at $\sqrt{s} = 161.3$ GeV and $\sqrt{s} = 172.1$ GeV with $n\leq 3\,\gamma$ correspond to values of the total measured cross-sections of:

$$\sigma_{\gamma\gamma(\gamma)}(\sqrt{s} = 161.3 \text{ GeV}) \;=\; 16.2 \pm 1.4\,\text{pb}$$

and

$$\sigma_{\gamma\gamma(\gamma)}(\sqrt{s} = 172.1 \text{ GeV}) \;=\; 13.9 \pm 1.3\,\text{pb}$$

when at least two photons are in the range $16^\circ < \theta_\gamma < 164^\circ$. The quoted error is purely statistical. The possible systematic effects have been found to be much smaller than the statistical errors and are neglected. The same holds for the error on the measured luminosity and for the error associated to the contribution of the different sources of background. The predicted cross-sections for the process $e^+e^-\to\gamma\gamma(\gamma)$ at the two centre-of-mass energies are $16.40 \pm 0.09$ pb and $14.25 \pm 0.09$ pb [6] respectively, in good agreement with the observed values.

The two measured cross-sections are shown in Figure 4 as a function of the centre-of-mass energy together with the prediction of QED and our previously determined values at $\sqrt{s} = 91.2$ GeV [1] and $\sqrt{s} = 133.3$ GeV [2].

# 4 Limits on deviations from QED

The possible deviations from QED are parametrised in terms of effective Lagrangians, and their effect on the observables can be expressed as a multiplicative correction term to the QED

1) The polar angle $\theta^*$ of the event is defined as $\cos\theta^* = |\sin(\frac{\theta_1-\theta_2}{2})/\sin(\frac{\theta_1+\theta_2}{2})|$, where $\theta_1$ and $\theta_2$ are the polar angles of the two most energetic photons in the event.

differential cross-section. Depending on the type of parametrisation two general forms are considered:

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

and

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

which depend on the centre-of-mass energy, the polar angle $\theta$ and the scale parameter $\Lambda$ which has dimension of energy. A simpler and more standard way of parametrising the deviations from QED is the introduction of the cut-off parameters $\Lambda_\pm$ [7]. The differential cross-section can be obtained from equation 1 by replacing $\Lambda^4$ by $\pm(2/\alpha)\Lambda^4_\pm$.

Limits on the different scale parameters have already been set in our previous publication [2]. However, since the sensitivity to possible deviations from QED increases rapidly with the centre-of-mass energy they are improved with the present data. In order to quantify the possible deviations from QED we define, for each sample at a given centre-of-mass energy, a likelihood for the different hypotheses of $\Lambda$ in terms of the observed polar angle of the event ($\theta_i$) and the total number of observed events ($N_0$) as:

$$L(\lambda_p) = \frac{1}{\sqrt{2\pi}\sigma(\lambda_p)} exp\left(\frac{-(N_o - N_t(\lambda_p))^2}{2\sigma^2(\lambda_p)}\right) \prod_{i=1}^{N_o} f(\cos\theta_i|\lambda_p) \tag{3}$$

In this expression $\lambda_p$ stands for the parameter under consideration ($1/\Lambda^4$ or $1/\Lambda'^6$); $N_t(\lambda_p)$ is the total number of expected events, $\sigma(\lambda_p)$ the statistical error on the number of expected events and $f(\cos\theta_i|\lambda_p)$ the probability density function of the polar angle $\theta$. The choice of $\lambda_p$ as a parameter has the advantage of giving, to a good approximation, a parabolic shaped log-likelihood around the maximum. The estimated parameters from the combined data samples at the two centre-of-mass energies are:

$$\begin{aligned} \frac{1}{\Lambda^4} &= \left(-0.03^{+0.11}_{-0.10}\right) 10^{-11} \quad \mathrm{GeV}^{-4} \\ \frac{1}{\Lambda'^6} &= \left(-0.11^{+0.32}_{-0.30}\right) 10^{-16} \quad \mathrm{GeV}^{-6} \end{aligned}$$

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:

$$\begin{aligned} \Lambda &> 844 \quad \mathrm{GeV} \\ \Lambda_+ &> 207 \quad \mathrm{GeV} \\ \Lambda_- &> 205 \quad \mathrm{GeV} \\ \Lambda' &> 507 \quad \mathrm{GeV} \end{aligned}$$

Another way to study possible deviations from QED is to postulate the existence of an excited electron ($e^*$) of mass $m_{e^*}$ which couples to the electron and the photon via magnetic interactions. To describe this interaction two different phenomenological Lagrangians are used; one with a magnetic interaction [8]:

$$\mathcal{L} = \frac{e}{2\Lambda_{e^*}} \overline{\Psi}_{e^*} \sigma^{\mu\nu} \Psi_e F_{\mu\nu} + h.c. \tag{4}$$

and another one with a magnetic interaction where only left-handed or right-handed fermions are involved [9]:

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

In both cases $\Lambda_{e^*}$ is related to the effective scale of the interaction and $m_{e^*}$ is the additional mass parameter. Fixing the interaction scale $\Lambda_{e^*}$ to $m_{e^*}$ we obtain

$$\frac{1}{m_{e^*}^4} = \left(-0.10^{+\,0.28}_{-\,0.28}\right)\ 10^{-9} \quad \mathrm{GeV}^{-4}$$

for the first case and

$$\frac{1}{m_{e^*}^4} = \left(-0.25^{+\,0.78}_{-\,1.04}\right)\ 10^{-9} \quad \mathrm{GeV}^{-4}$$

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

$$m_{e^*} > 210 \quad \mathrm{GeV}$$

and

$$m_{e^*} > 157 \quad \mathrm{GeV}$$

respectively.

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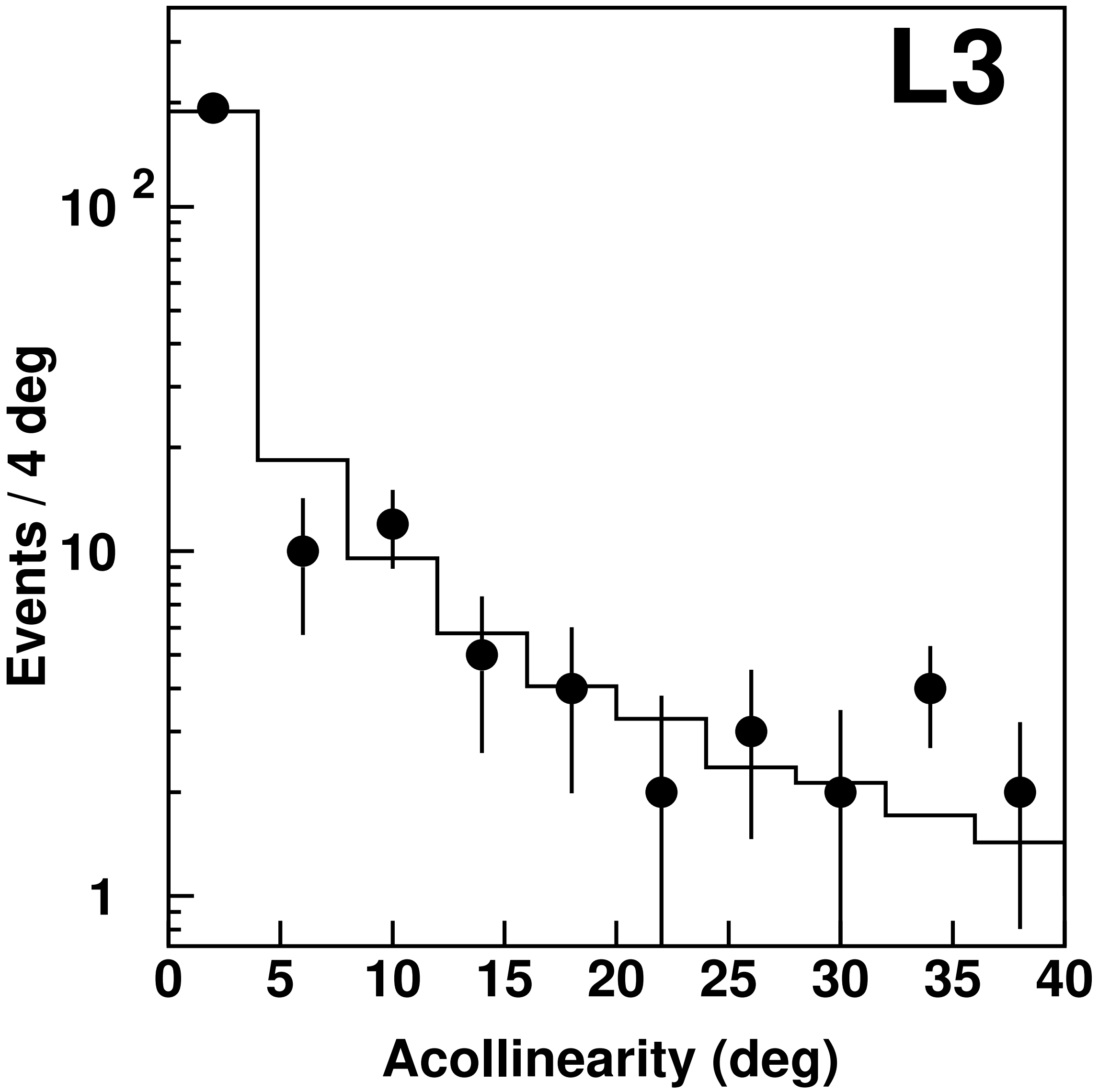


Figure 1: Distribution of the acollinearity angle between the two most energetic photons in the $e^+e^- \to \gamma\gamma(\gamma)$ process. Data samples at $\sqrt{s} = 161.3$ and $\sqrt{s} = 172.1$ GeV have been combined. The points are data and the histogram is the Monte Carlo prediction.

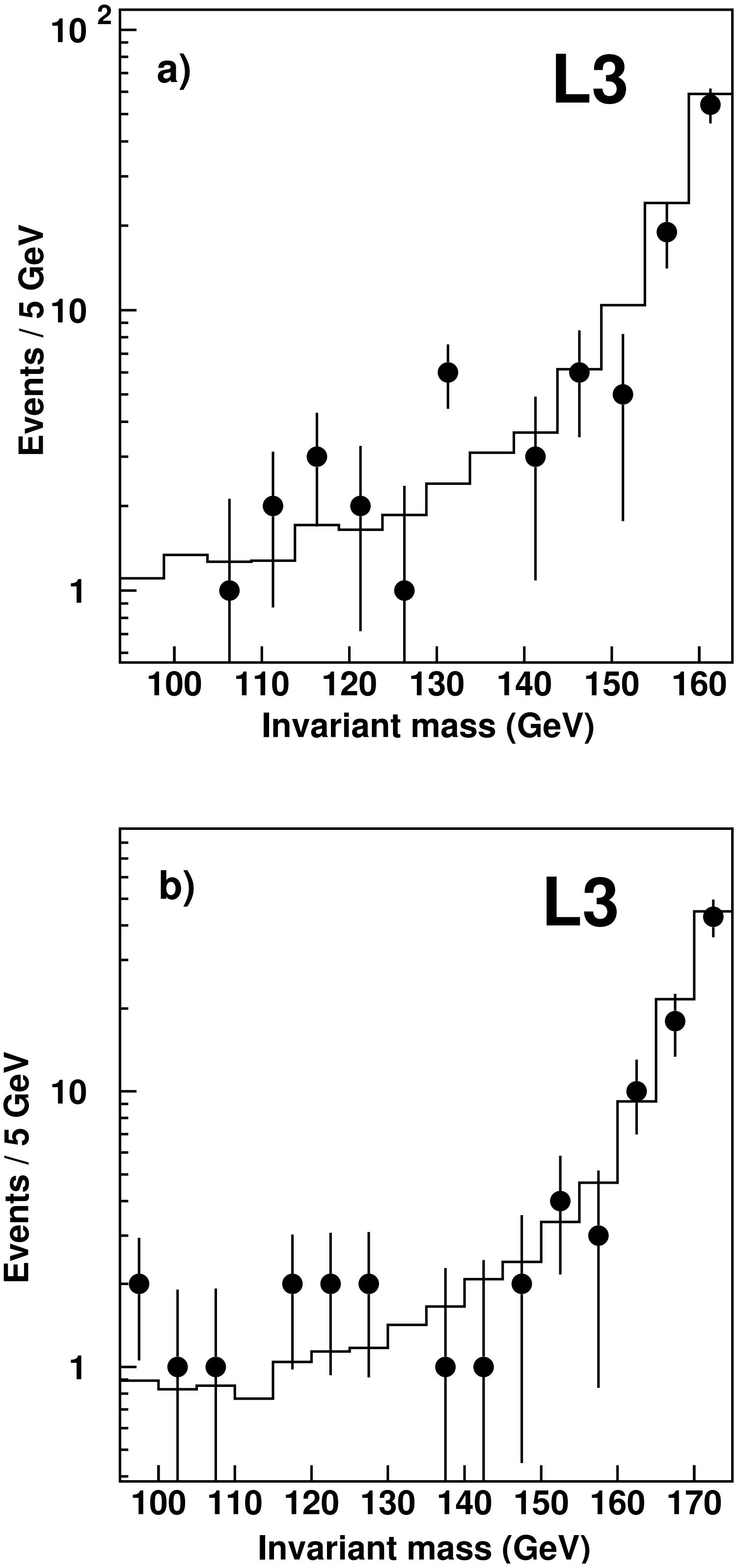


Figure 2: Distribution of the invariant mass of the two most energetic photons of the process $e^+e^-\rightarrow n\gamma\,(n\geq 2)$ for $\sqrt{s} = 161$ GeV (a) and 172 GeV (b). The points are data and the histogram is the Monte Carlo prediction.

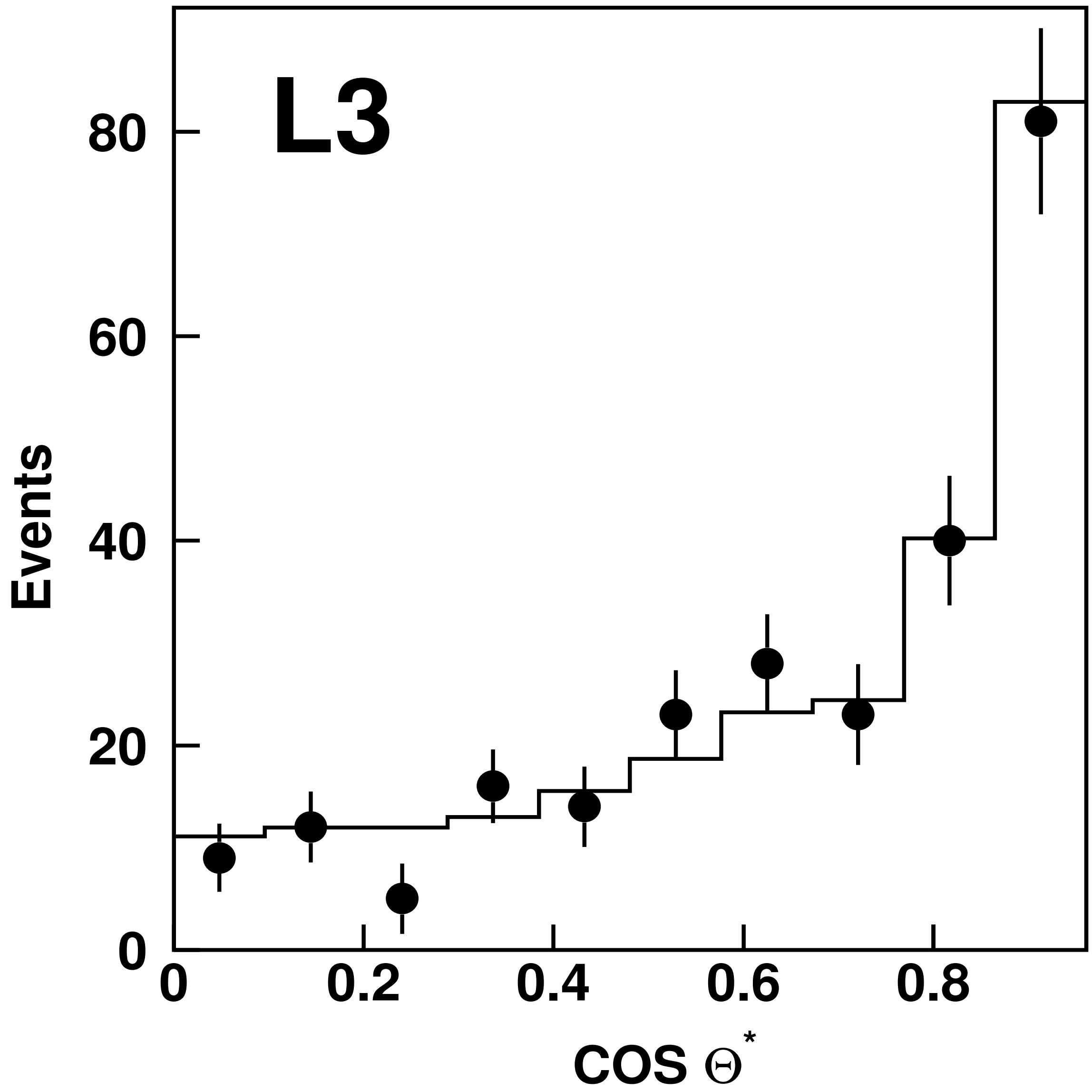


Figure 3: Distribution of the polar angle of the event for the selected $e^+e^- \to \gamma\gamma(\gamma)$ sample. Data samples at $\sqrt{s} = 161.3$ and $\sqrt{s} = 172.1$ GeV have been combined. The points are data and the histogram is the Monte Carlo prediction.

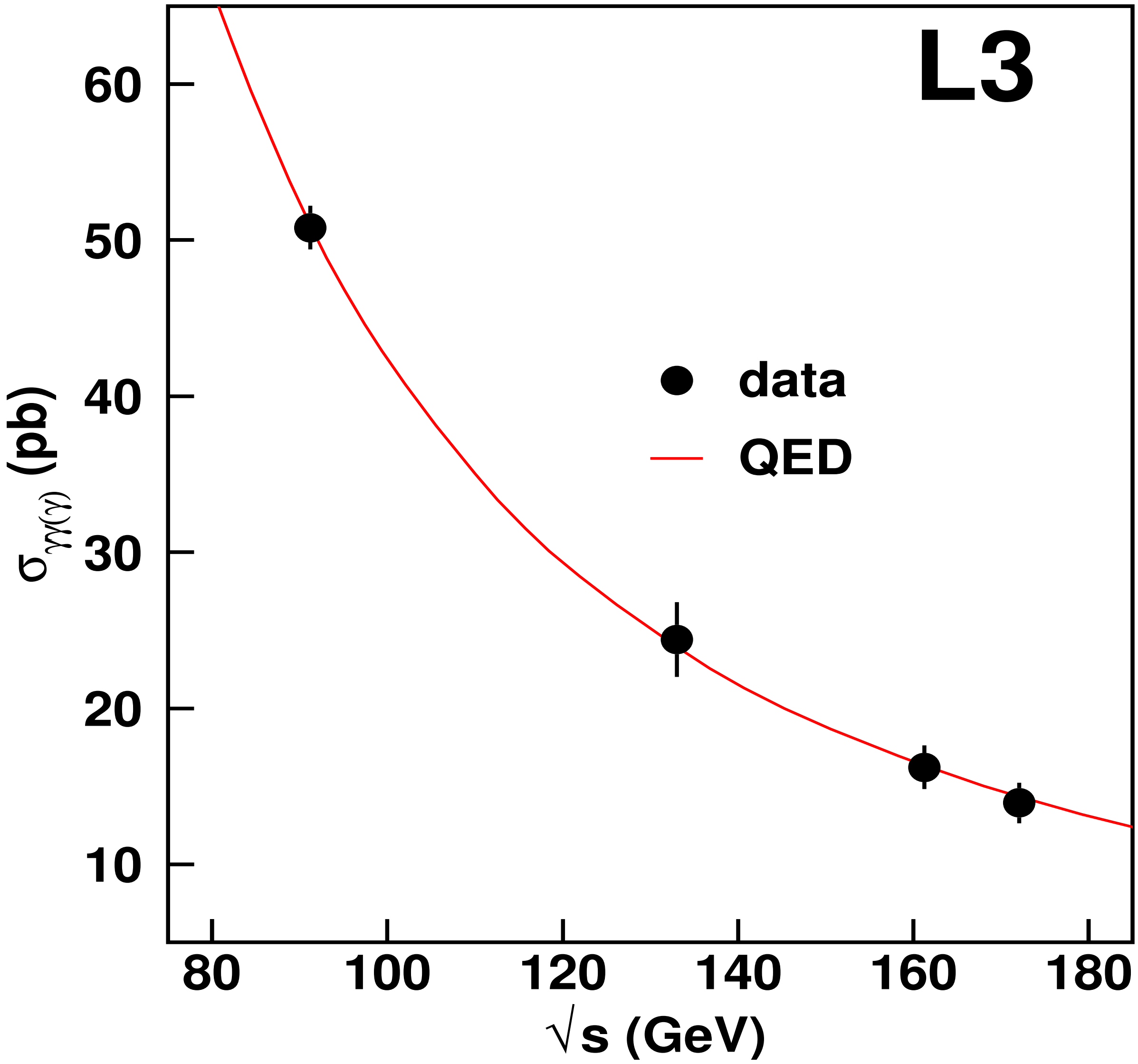


Figure 4: Measured cross-sections as function of the centre-of-mass energy for $\theta_\gamma$ between $16^\circ$ and $164^\circ$ compared with the QED prediction. The value at $\sqrt{s} = 90$ GeV has been extrapolated to the aforementioned angular range from the one given in [1].