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Measurement of Quasi-Real Compton Scattering at LEP

The L3 Collaboration

Abstract

We report on a study of quasi-real Compton scattering at centre-of-mass energies between 20 GeV and 185 GeV using the L3 detector at LEP. The analysis is based on data corresponding to an integrated luminosity of $634.7\,\mathrm{pb}^{-1}$ recorded at LEP centre-of-mass energies between 89 GeV and 202 GeV. A total of 7335 Compton scattering events are collected. Total and differential cross sections are presented and found to be in good agreement with QED expectations. The measurement of Compton scattering is used to derive exclusion limits on the coupling λ for the on-shell production of an excited electron $\mathrm{e}^{\star}$ decaying into a $\gamma\mathrm{e}$ pair in the mass range $20\ \mathrm{GeV} < m_{\mathrm{e}^{\star}} < 200\ \mathrm{GeV}$. The results presented in this note are preliminary.

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Introduction

Due to the effect of initial-state bremsstrahlung, lower energy beam electrons[1)] are produced accompanied by a high energy photon collinear to the beam direction. Either the electron or the photon can react with the other beam particle in a hard scattering process, resulting in either Bhabha or Compton scattering. Both reactions are illustrated in Figure 1. The process of quasi-real Compton scattering has been studied at centre-of-mass energies, $\sqrt{s}$, between 88 GeV and 189 GeV [1,2]. This note summarizes the preliminary results including the data collected with the L3 detector at energies between 192 GeV and 202 GeV.

The cross section of quasi-real Compton scattering is described by the following convolution given by [3]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}s'} = f_{\gamma\mathrm{e}}(s', s)\, \sigma_{\gamma\mathrm{e}}^{\mathrm{QED}}(s') \; .$$

At lowest order, $\mathcal{O}(\alpha^3)$, the Compton cross section at Born-level, $\sigma_{\gamma\mathrm{e}}^{\mathrm{QED}}$, is folded with the equivalent photon spectrum, $f_{\gamma\mathrm{e}}$. The spectrum of the effective centre-of-mass energy of electron and photon, $\sqrt{s'}$, of the selected events is then used to measure the unconvoluted Compton cross section at a reduced centre-of-mass energy.

In the following the analysis of the L3 data taken at the Z resonance and at energies up to 202 GeV is described and the measurement of the total and the differential cross sections of Compton scattering are presented.

The Compton scattering process in particular is sensitive to the production of an on-shell excited electron, $\mathrm{e}^\star$, decaying into an electron-photon pair. The measurements are used to derive upper limits on the $\mathrm{e}^\star\mathrm{e}\,\gamma$ coupling for masses of the excited electron almost up to the centre-of-mass energy of the $\mathrm{e}^+\mathrm{e}^-$ collision, covering a mass range from 20 GeV to 200 GeV.

Analysis Techniques

Electron Photon Identification

The L3 detector and its performance is described elsewhere [4]. The Monte Carlo prediction of Compton scattering is based on Monte Carlo events generated with the program TEEGG [5], taking into account corrections of order $\mathcal{O}(\alpha^4)$. The following Monte Carlo event generators are used to simulate the various background reactions: BHAGENE3 [6] and BHWIDE [7] ($\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{e}^+\mathrm{e}^-(\gamma)$), KORALZ [8] ($\mathrm{e}^+\mathrm{e}^- \rightarrow \tau^+\tau^-(\gamma)$), GGG [9] ($\mathrm{e}^+\mathrm{e}^- \rightarrow \gamma\gamma(\gamma)$) and DIAG36 [10] ($\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+\mathrm{e}^-$). The response of the L3 detector is modelled with the GEANT [11] detector simulation program.

The identification of electrons and photons requires clusters in the electromagnetic calorimeter with an energy larger than 5 GeV and consistent with an electromagnetic shower shape. A cluster is defined as an electron, if

- there is a reconstructed track within 5° to the cluster direction in azimuthal angle ϕ,
- or if more than 20% of the signals expected for an electron are present in the vertex chamber within a 1 cm wide road in the $r-\phi$ plane centred around the cluster direction.

A cluster is defined as a photon, if

1) If not mentioned otherwise, electron refers to both electron and positron.

- it is not identified as an electron,
- and the separation to the next electron candidate is larger than 8°.

Reconstruction of the Effective Centre-of-Mass Energy

For three-particle final states the particle momenta are obtained from the measured directions using energy and momentum conservation. Assuming that one undetected particle, either an electron or a photon, is radiated along the beam axis, its energy, E_{mis}, is given by the polar angles, θ_1 and θ_2, of the detected particles:

$$E_{\mathrm{mis}} = \sqrt{s}\frac{|\sin(\theta_1+\theta_2)|}{\sin\theta_1+\sin\theta_2+|\sin(\theta_1+\theta_2)|} \ . \tag{1}$$

In this case, the energies of the scattered particles, E_1^a and E_2^a, are also determined by the polar angles:

$$E_{1,2}^a = \sqrt{s}\frac{\sin(\theta_{2,1})}{\sin\theta_1+\sin\theta_2+|\sin(\theta_1+\theta_2)|} \ . \tag{2}$$

The effective centre-of-mass energy of the hard scattering process is calculated using the energy of the missing particle:

$$s' = s\left(1-2\frac{E_{\mathrm{mis}}}{\sqrt{s}}\right) \ . \tag{3}$$

This procedure improves the resolution on s' as compared to the direct energy measurement. This is particularly important for data taken at $\sqrt{s}\approx m_{\mathrm{Z}}$ where the radiative part of the cross section is small.

Compton Scattering of Quasi-Real Photons

Event Selection

In case of quasi-real Compton scattering one of the incoming beam electrons remains inside the beam pipe and is not detected. The energy depositions in the calorimeter are caused by the Compton scattered electron and photon.

For the selection of Compton scattering events both electron and photon are required to be observed within $|\cos\theta|<0.94$. The scattering angle in the centre-of-mass system of the γe pair has to lie inside $|\cos\theta^*|<0.8$ to reduce the contribution from low angle Bhabha scattering.

The ratio E_1/E_1^a is required to be greater than 0.7. All events containing a third electromagnetic cluster with an energy larger than 2 GeV and an angular separation of more than 8° from the identified electron are removed. To ensure the selection of quasi-real photons, the transverse momentum of the final state system has to be lower than 15% of the beam energy. This cut restricts the momentum transfer to the photon, suppressing the contribution from off-shell photons. The photons of the remaining sample have an average Q^2 between 2 GeV^2 and 9 GeV^2 dependent on the centre-of-mass energy resulting in a small average virtuality Q^2/s' of the order 10^{-3}.

Higher background contributions are expected when the effective centre-of-mass energy is close to $\sqrt{s}$ from either photon conversion in the reaction $\mathrm{e^+e^-}\rightarrow\gamma\gamma(\gamma)$ in case that the two resulting tracks are not resolved or from Bhabha scattering if one track is lost. To remove these backgrounds the energy of the lower energetic cluster of the γe pair, E_2, is required to be less than 85% of the beam energy. The distributions of $E_2/E_{\rm beam}$ are shown in Figures 2a and 2b. Figure 3 shows the resulting $\sqrt{s'}$-distributions for Compton scattering for LEP centre-of-mass energies between 189 GeV and 202 GeV. All distributions are found to be in good agreement with the Monte Carlo expectations. The total cross sections at reduced centre-of-mass energies are derived from the combined distribution.

Total Cross Sections

In total 7335 candidates for Compton scattering are selected from the data sample. The Born cross section at an effective centre-of-mass energy is measured by scaling the theoretical cross section, $\sigma^{\rm QED}_{\gamma\rm e}$, with the ratio between the number of selected events, $N_{\gamma\rm e}$, corrected for the expected background, $N^{\rm MC}_{\rm bg}$, and the Monte Carlo prediction for Compton scattering, $N^{\rm MC}_{\gamma\rm e}$:

$$\sigma(\langle\sqrt{s'}\rangle) = \sigma^{\rm QED}_{\gamma\rm e}(\langle\sqrt{s'}\rangle)\frac{N_{\gamma\rm e} - N^{\rm MC}_{\rm bg}}{N^{\rm MC}_{\gamma\rm e}} \ . \qquad (4)$$

The value $\langle\sqrt{s'}\rangle$ is the mean of the reconstructed effective centre-of-mass energies of the data in the corresponding energy bin. The background contributions from Bhabha scattering and from the process $\rm e^+e^- \rightarrow \gamma\gamma(\gamma)$ are found to be less than 0.5% of the expected events.

Table 2 contains the numbers of selected events, $N_{\gamma\rm e}$, and the measured total cross sections of Compton scattering for 14 different $\sqrt{s'}$ bins. The quoted systematic error is dominated by the limited Monte Carlo statistics. Figure 4a shows the results compared with the QED prediction for the Compton scattering cross section. The measurements are in good agreement with the theoretical prediction.

Differential Cross Section

The scattering angle, θ^*, of the electron in the centre-of-mass system is given in the case of $\gamma\rm e^-$ scattering by:

$$\cos\theta^* = \frac{\sin(\theta_\gamma - \theta_{\rm e^-})}{\sin\theta_\gamma + \sin\theta_{\rm e^-}} \ .$$

Since the polar angles θ_γ and $\theta_{\rm e^-}$ are measured with respect to the direction of the incoming electron ($\rm e^-$), the scattering angle is defined by $\pi - \theta^*$ in case of $\gamma\rm e^+$ scattering.

Combining all energy bins from 20 GeV to 80 GeV the differential cross section of Compton scattering is derived. The results are shown in Figure 4b. The measurement exhibits the preference for backward scattering in the centre-of-mass system, which is characteristic for unpolarized Compton scattering.

Production of Single Excited Electrons

Models including excited leptons [12] predict that the production of excited electrons in $\rm e^+e^-$ collisions is extremely peaked in the forward direction. Therefore, the electron in the process $\rm e^+e^- \rightarrow e\, e^\star$ can be lost in the beam pipe whereas the γe decay products of the excited electron would be seen inside the detector. Consequently, an exclusion limit on the production of excited electrons can be derived from the measurement of Compton scattering.

Within the theoretical model for excited leptons, the coupling $\mathrm{e}^\star\mathrm{e}\,\gamma$ is described by one dimensionless parameter λ [13]. The cross section for the production of an excited electron $\mathrm{e}^\star$ in electron-photon collisions, decaying into an γe pair is then given by [14]:

$$\sigma(\mathrm{e}\,\gamma \to \mathrm{e}^\star \to \mathrm{e}\,\gamma)(m_{\mathrm{e}^\star}) = \frac{4\pi^2\alpha\,\lambda^2}{m_{\mathrm{e}^\star}^2}\frac{\Gamma(\mathrm{e}^\star \to \mathrm{e}\,\gamma)}{\Gamma_{\mathrm{e}^\star}} \quad .$$

This expression is valid assuming a narrow width for the excited electron. The partial width for the radiative decay is given by [14]:

$$\Gamma(\mathrm{e}^\star \to \mathrm{e}\,\gamma) = \frac{1}{2}\lambda^2\alpha\, m_{\mathrm{e}^\star} \quad .$$

The total width, $\Gamma_{\mathrm{e}^\star}$, also takes into account the partial widths for the decays $\mathrm{e}^\star \to \nu\mathrm{W}$ and $\mathrm{e}^\star \to \mathrm{e}\,\mathrm{Z}$ for masses $m_{\mathrm{e}^\star}$ above the masses of the W and Z bosons [15].

Within an interval $m_{\mathrm{e}^\star} \pm \Delta$, the number of observed γe pairs and the expected contribution from Compton scattering, $N_{\gamma\mathrm{e}}$, are determined. These numbers are used to calculate the 95% confidence level upper limit for the number of events that could come from such a narrow $\mathrm{e}^\star$ resonance, $N_{\mathrm{e}^\star}$. The interval width Δ is chosen as twice the invariant mass resolution of typically 1%. Taking into account the expected angular distribution in the $\mathrm{e}^\star$ rest frame [12],

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \frac{1+\cos\theta}{2} \quad ,$$

the upper limit for the coupling λ is determined by satisfying the inequality

$$\frac{N_{\mathrm{e}^\star}}{N_{\gamma\mathrm{e}}}\sigma_{\gamma\mathrm{e}}^{\mathrm{QED}}(m_{\mathrm{e}^\star}) > \frac{\epsilon_{\mathrm{e}^\star}}{\epsilon_{\gamma\mathrm{e}}}\frac{\pi^2\,\alpha\,\lambda^2}{2\,m_{\mathrm{e}^\star}\Delta}\left(c_{\max} - c_{\min} + \frac{c_{\max}^2 - c_{\min}^2}{2}\right)\frac{\Gamma(\mathrm{e}^\star \to \mathrm{e}\,\gamma)}{\Gamma_{\mathrm{e}^\star}} \quad .$$

This uses the QED prediction for the Compton scattering cross section, $\sigma_{\gamma\mathrm{e}}^{\mathrm{QED}}$, at an effective centre-of-mass energy given by the mass $m_{\mathrm{e}^\star}$. The limit on the coupling parameter λ takes into account the efficiencies $\epsilon_{\mathrm{e}^\star}$ and $\epsilon_{\gamma\mathrm{e}}$ and the acceptance cuts in the $\mathrm{e}^\star$ rest frame, $c_{\min} < \cos\theta^* < c_{\max}$.

The result is shown in Figure 5. A comparable limit has been derived from our dedicated search for excited electrons based on data collected at energies up to 189 GeV [16]. Other searches for excited electrons at LEP are reported in [17]. For comparison, the upper limit for the $\mathrm{e}^\star\mathrm{e}\,\gamma$ coupling from our analysis of the QED reaction $\mathrm{e}^+\mathrm{e}^- \to \gamma\gamma(\gamma)$ is also shown [18]. From our analysis of the pair production $\mathrm{e}^\star\mathrm{e}^\star$ in the channel ee$\gamma\gamma$, a lower mass limit of 94.2 GeV at 95% confidence level is derived [16]. The results from previous experiments using the process of quasi-real Compton scattering at $\mathrm{e}^+\mathrm{e}^-$ colliders [19] and the upper limits from the experiments at the HERA ep collider [20] are included for comparison.

Conclusions

Electron-photon events are identified as Compton scattering of quasi-real photons. We measure this process in the centre-of-mass energy range from 20 GeV to 185 GeV. The total rate and the observed differential cross sections are in good agreement with the theoretical expectations.

An upper limit for a hypothetical coupling $\mathrm{e}^\star\mathrm{e}\,\gamma$ as a function of $m_{\mathrm{e}^\star}$ is derived from the measurement of Compton scattering. No indications for the existence of an excited electron are found in the data. The 95% confidence level limit on the coupling parameter λ is of the order 10^{-2} to 10^{-1} for the mass region 20 GeV $< m_{\mathrm{e}^\star} <$ 200 GeV.

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$\sqrt{s}$ [GeV]	$\int\mathcal{L}\mathrm{d}t$ [pb^{-1}]	$N_{\gamma\mathrm{e}}$
88 − 93	143.9	3877
130	6.4	83
136	6.0	81
161	10.8	108
172	10.1	82
183	55.0	404
189	176.4	1272
192	29.4	178
196	83.5	538
200	76.3	471
202	36.9	241

Table 1: Integrated luminosities recorded at the various centre-of-mass energies and the number of selected quasi-real Compton scattering events, $N_{\gamma\mathrm{e}}$.

$\sqrt{s'}$ [GeV]	$\langle\sqrt{s'}\rangle$ [GeV]	$N_{\gamma\mathrm{e}}$	$\sigma_{\gamma\mathrm{e}} \pm$ (stat.) $\pm$ (syst.) [pb]	$\sigma_{\gamma\mathrm{e}}^{\mathrm{QED}}$ [pb]
< 25	21.0	1372	$788.3 \pm 20.7 \pm 5.8$	767.5
25 − 35	29.8	1224	$365.1 \pm 10.9 \pm 2.9$	381.0
35 − 45	40.1	1342	$206.4 \pm 5.8 \pm 2.0$	210.8
45 − 55	49.5	975	$130.8 \pm 4.4 \pm 1.6$	138.4
55 − 65	59.7	701	$95.7 \pm 3.6 \pm 1.4$	95.1
65 − 75	69.6	523	$69.1 \pm 3.1 \pm 1.2$	69.9
75 − 85	79.4	372	$56.5 \pm 2.8 \pm 1.2$	53.7
85 − 100	91.6	308	$39.1 \pm 2.3 \pm 1.0$	40.4
100 − 115	106.8	218	$33.6 \pm 2.0 \pm 0.9$	29.7
115 − 130	121.6	126	$23.3 \pm 2.1 \pm 0.9$	22.9
130 − 145	137.3	86	$19.7 \pm 2.0 \pm 0.9$	18.0
145 − 160	152.2	51	$14.6 \pm 2.1 \pm 1.0$	14.6
160 − 175	165.8	30	$16.0 \pm 2.3 \pm 1.2$	12.3
175 − 200	184.2	7	$10.4 \pm 4.0 \pm 2.1$	10.0

Table 2: Number of selected $\gamma\mathrm{e} \rightarrow \gamma\mathrm{e}$ events, $N_{\gamma\mathrm{e}}$, for the various ranges of $\sqrt{s'}$ and their average $\langle\sqrt{s'}\rangle$. The corresponding measured cross sections, $\sigma_{\gamma\mathrm{e}}$, and their statistical and systematic errors are listed and compared to the QED cross sections, $\sigma_{\gamma\mathrm{e}}^{\mathrm{QED}}$.

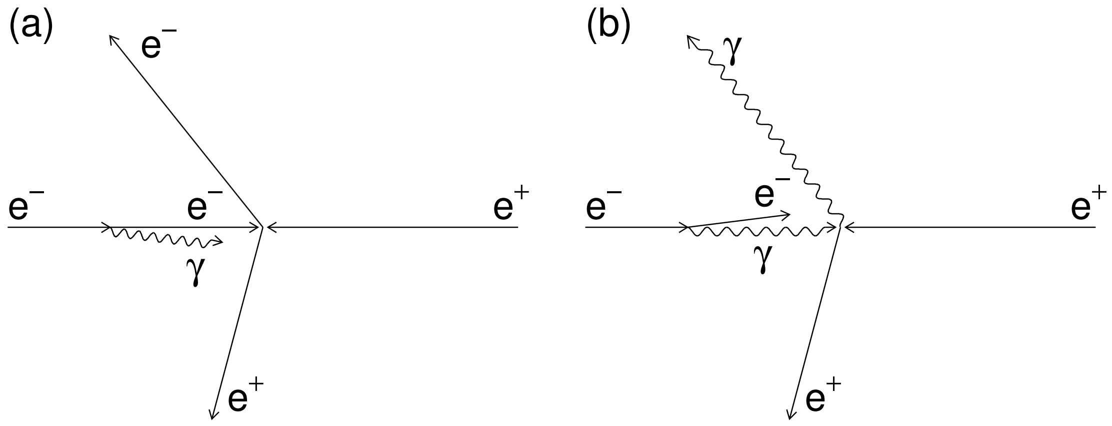

Figure 1: Schematic representation of initial-state radiation at e^+e^- colliders for (a) radiative Bhabha scattering and (b) Compton scattering of quasi-real photons.

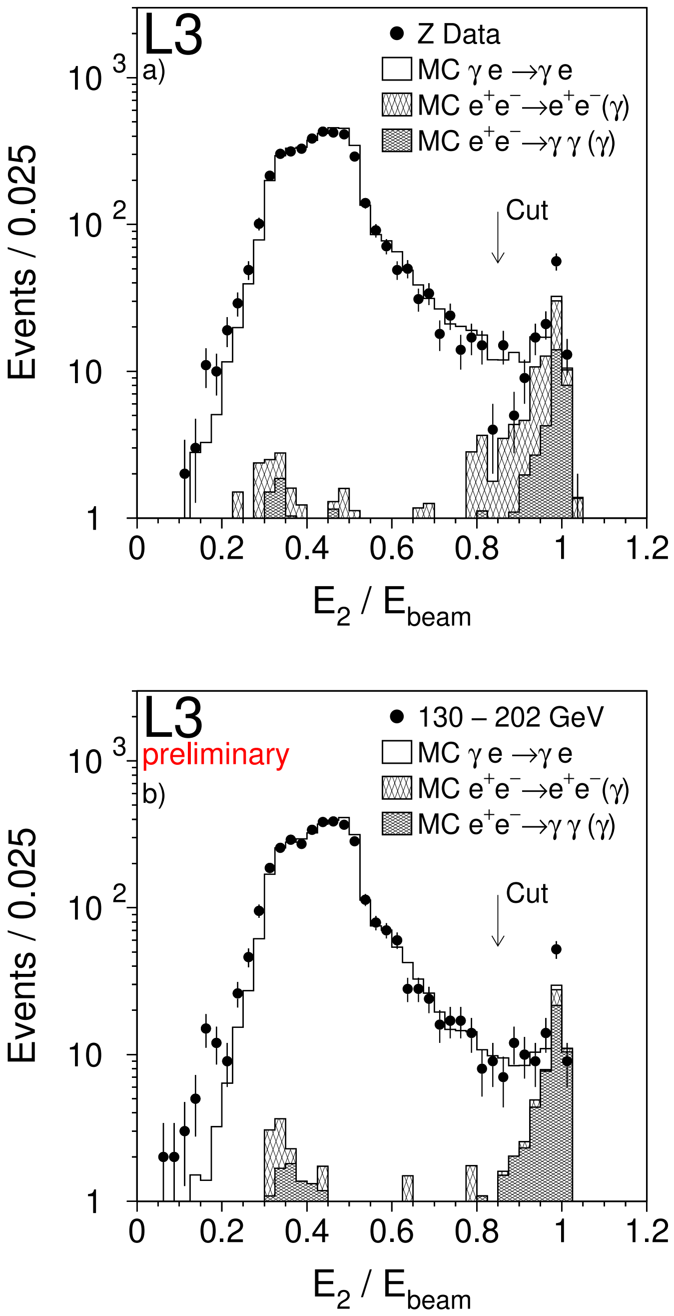

Figure 2: The measured energy distributions of the second electromagnetic cluster, E_2, normalized to the beam energy, E_{beam}, for Compton scattering events (a) at the Z peak and (b) in the LEP2 energy range as indicated. Data and Monte Carlo simulation for signal and background are shown. All other selection cuts are applied.

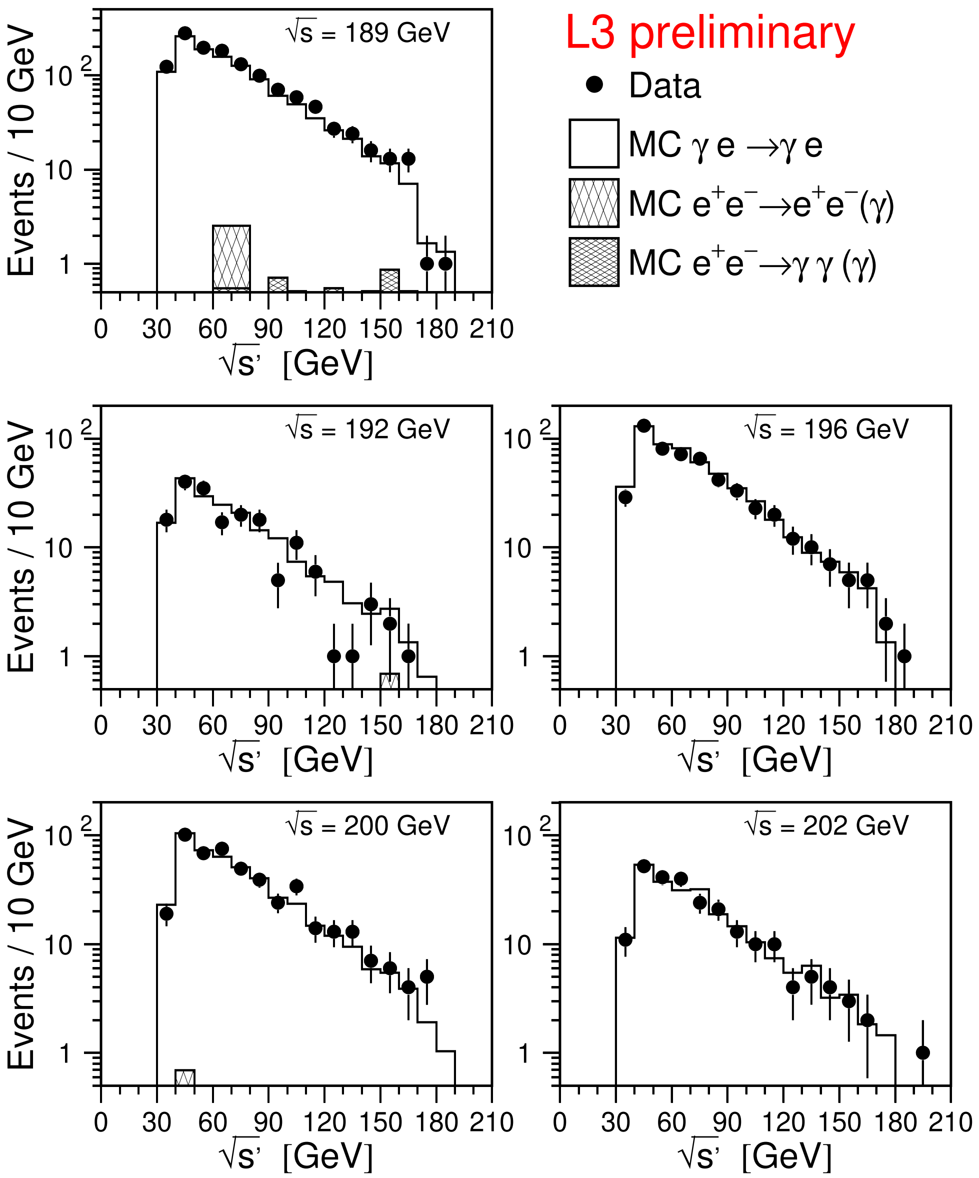

Figure 3: The $\sqrt{s'}$ spectra of Compton scattering for data and Monte Carlo simulation for signal and background are shown for different centre-of-mass energies between 189 GeV and 202 GeV. All selection cuts are applied.

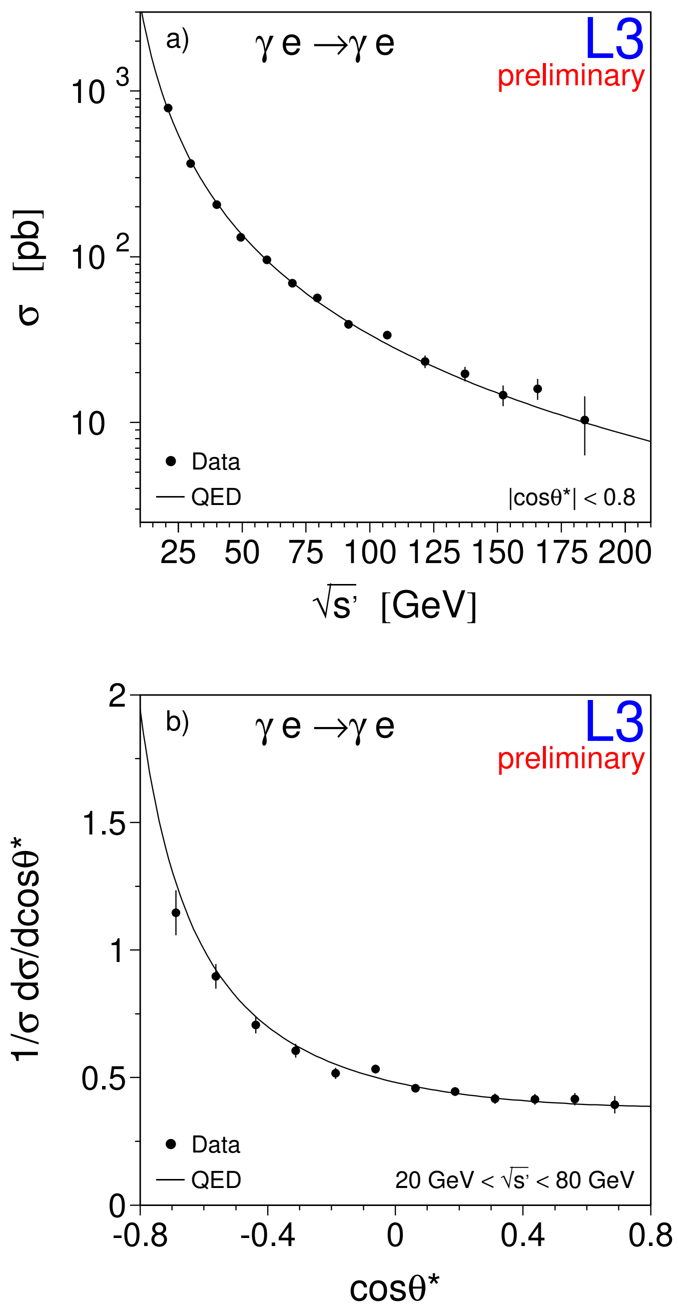

Figure 4: (a) Measured total cross sections of Compton scattering inside the angular range $|\cos\theta^*| < 0.8$ as a function of the effective centre-of-mass energy $\sqrt{s'}$. The solid line shows the QED prediction. (b) The differential cross section of Compton scattering as a function of the scattering angle in the γe rest frame. The solid line shows the QED prediction.

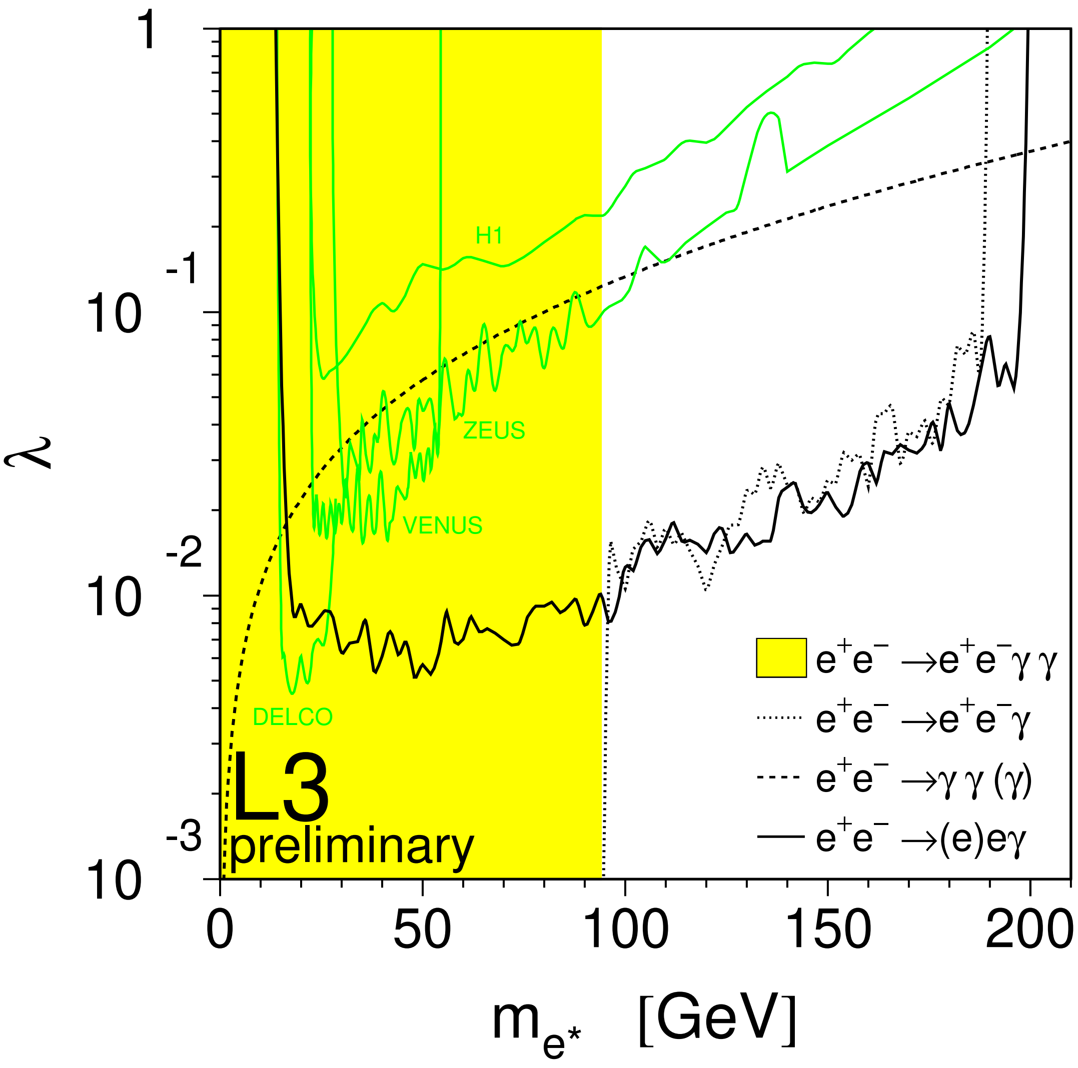

Figure 5: The upper limit of the coupling constant λ at 95% confidence level as a function of $m_{e^\star}$, derived from the measurement of Compton scattering (solid black line), covering the mass range up to 200 GeV. The dashed line shows the analogous result from our previous analysis of the process $e^+e^- \to \gamma\gamma(\gamma)$, based on the data recorded at centre-of-mass energies at 183 GeV and 189 GeV [18]. Using data collected at energies up to 189 GeV, excited electrons with masses up to 94.2 GeV at 95% confidence level are excluded from our analysis of the pair production $e^\star e^\star$ in the channel $e\,e\,\gamma\gamma$ (shaded area), and an upper limit on the coupling λ is also derived from our search for the single production of an excited electron (dotted line) [16]. The results from other collider experiments are included as indicated [19, 20].