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# Production of Single W Bosons at LEP

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## Abstract

We report on the observation of single W boson production in a data sample collected by the L3 detector at LEP2. The signal consists of large missing energy final states with a single energetic lepton or two hadronic jets. The cross-section is measured to be $0.61^{+0.43}_{-0.33} \pm 0.05$ pb at the centre of mass energy $\sqrt{s} = 172$ GeV, consistent with the Standard Model expectation. From this measurement the following limits on the anomalous $\gamma$WW gauge couplings are derived at 95% CL: $-3.6 < \Delta\kappa_\gamma < 1.5$ and $-3.6 < \lambda_\gamma < 3.6$.

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# 1 Introduction

The Standard Model of electroweak interactions [1] is successful in describing gauge boson couplings to fermions. Extensive studies of Zff couplings have been performed at LEP in the vicinity of the Z pole [2]. The increase of the LEP energy above the $\mathrm{W^+W^-}$ production threshold makes it possible to examine triple gauge boson couplings [3]. Limits on the anomalous couplings have been already reported by the experiments at hadron colliders [4–6] and at LEP [7, 8].

Studies of anomalous couplings at LEP have so far focused on the process $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-}$, where it is difficult to disentangle the effects of ZWW and $\gamma$WW couplings. A measurement of the single W production [9] [1)]

$$\mathrm{e^+e^-} \rightarrow \mathrm{e^+}\nu_\mathrm{e}\mathrm{W^-} \qquad (1)$$

constitutes a clean test of the $\gamma$WW vertex [10]. This process is dominated by contributions from the three diagrams shown in Figure 1.

The deviation of the gauge boson couplings from their Standard Model values is usually described in terms of five parameters: $\Delta g_1^\mathrm{Z}$, $\Delta\kappa_\mathrm{Z}$, $\Delta\kappa_\gamma$, $\lambda_\mathrm{Z}$ and $\lambda_\gamma$. The cross-section of process (1) is shown in reference [9] to depend only on the $\Delta\kappa_\gamma$ and $\lambda_\gamma$ parameters.

A specific feature of this reaction is a final state positron (electron) produced at very low polar angle and therefore not detected. Thus the signature of this process is large transverse missing energy and either a single energetic lepton, if the W boson decays into lepton and neutrino, or two hadronic jets in case of hadronic W decays. This process constitutes a background to missing energy searches for new physics beyond the Standard Model. No measurement of single W production has so far been reported at LEP.

In this paper we present a measurement of the cross section for the process $\mathrm{e^+e^-} \rightarrow \mathrm{e^+}\nu_\mathrm{e}\mathrm{W^-}$ using both leptonic and hadronic decays of W bosons. From this observation we derive limits on the anomalous $\gamma$WW couplings.

# 2 Data and Monte Carlo Samples

The data were collected by the L3 detector at LEP in 1996. The integrated luminosities are 10.9 $\mathrm{pb^{-1}}$ at the centre of mass energy $\sqrt{s} = 161$ GeV and 10.2 $\mathrm{pb^{-1}}$ at $\sqrt{s} = 172$ GeV.

The L3 detector is described in reference [11]. Briefly, the $\mathrm{e^+e^-}$ collision point is surrounded by a precision silicon vertex detector, a time-expansion tracking chamber (TEC), a high resolution electromagnetic calorimeter (ECAL), a cylindrical shell of scintillation counters, a hadron calorimeter (HCAL), a muon spectrometer and a very forward calorimeter used for the luminosity measurements. The detector is installed in a large solenoidal magnet providing a 0.5 T field.

For the efficiency studies a sample of $\mathrm{e^+e^-} \rightarrow \mathrm{e^+}\nu_\mathrm{e}\mathrm{f}\,\bar{\mathrm{f}}'$ events was generated using the GRC4F [12] Monte Carlo generator. For the background studies the following Monte Carlo programs were used: KORALZ [13] ($\mathrm{e^+e^-} \rightarrow \mu^+\mu^-(\gamma)$, $\tau^+\tau^-(\gamma)$), KORALW [14] ($\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-} \rightarrow \mathrm{f}\,\bar{\mathrm{f}}'\mathrm{f}\,\bar{\mathrm{f}}'$), BHAGENE3 [15] ($\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}(\gamma)$), TEEGG [16] ($\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}\gamma$), PYTHIA [17] ($\mathrm{e^+e^-} \rightarrow \mathrm{q}\,\bar{\mathrm{q}}(\gamma)$), PYTHIA and PHOJET [18] ($\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-e^+e^-}$, $\mathrm{e^+e^-}\mu^+\mu^-$, $\mathrm{e^+e^-}\tau^+\tau^-$, $\mathrm{e^+e^-q\,\bar{q}}$), and EXCALIBUR [19] ($\mathrm{e^+e^-} \rightarrow \mathrm{f}\,\bar{\mathrm{f}}'\mathrm{f}\,\bar{\mathrm{f}}'$).

The Monte Carlo events are simulated in the L3 detector using the GEANT 3.15 program [20], which takes into account the effects of energy loss, multiple scattering and showering in

[1)] The charge conjugate reactions are understood to be included throughout the paper.

the detector. The GHEISHA program [21] is used to simulate hadronic interactions in the detector.

# 3 Analysis

In the analysis described below, the signal is defined as $\mathrm{e^+e^-} \rightarrow \mathrm{e^+}\nu_\mathrm{e}\,\mathrm{f}\,\bar{\mathrm{f}}'$ events that satisfy the following phase space requirements:

$$\begin{aligned} |\cos\theta_{\mathrm{e}^+}| &> 0.997 \\ \min(\mathrm{E_f}, \mathrm{E}_{\bar{\mathrm{f}}'}) &> 15 \text{ GeV} \\ |\cos\theta_{\mathrm{e}^-}| &< 0.75, \qquad \text{for } \mathrm{e^+}\nu_\mathrm{e}\mathrm{e^-}\bar{\nu}_\mathrm{e} \text{ events only} \end{aligned} \tag{2}$$

where $\theta_{e^+}$ ($\theta_{e^-}$) is the polar angle of the outgoing positron (electron), and $\mathrm{E_f}$ and $\mathrm{E}_{\bar{\mathrm{f}}'}$ are the fermion energies. The final states $\mathrm{e^+e^-} \rightarrow \mathrm{e^+}\nu_\mathrm{e}\,\mathrm{f}\,\bar{\mathrm{f}}'$ that do not satisfy these conditions are considered as a background; they consist mostly of the reaction $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-}$.

Inside the region of phase space (2) the single W production (process 1) dominates since it peaks strongly at $|\cos\theta_{\mathrm{e}^+}| \sim 1$. On average it accounts for 90% of all events in this region, the remaining 10% being mostly non-resonant final states. The purity depends slightly on the flavour of the $\mathrm{f}\,\bar{\mathrm{f}}'$ pair from $\mathrm{W^-}$ decays.

The above is illustrated in Figure 2 using a Monte Carlo sample of $\mathrm{e^+e^-} \rightarrow \mathrm{e^+}\nu_\mathrm{e}\mu^-\bar{\nu}_\mu$ final states. The cosine of the polar angle distribution, $\cos\theta_{\mathrm{e}^+}$, is shown in Figure 2a. The invariant mass distributions $\mathrm{M}_{\mu^-\bar{\nu}_\mu}$ and $\mathrm{M}_{\mathrm{e}^+\nu_\mathrm{e}}$ for events satisfying phase space conditions (2) are presented in Figures 2b and 2c. Only the $\mathrm{M}_{\mu^-\bar{\nu}_\mu}$ spectrum shows resonant behaviour at the W mass; the $\mathrm{M}_{\mathrm{e}^+\nu_\mathrm{e}}$ spectrum is clearly non-resonant since the positron does not originate from a W.

Due to the small data samples at the two centre of mass energies, the data are combined and the cross-section is quoted at $\sqrt{s} = 172$ GeV. The cross-section increases by a factor 1.20 from $\sqrt{s} = 161$ GeV to $\sqrt{s} = 172$ GeV according to the GRC4F predictions. The relative contribution of each final state to the signal is given by the corresponding cross-section and experimental selection efficiency. The selection efficiencies depend slightly on the amount of non-resonant contribution and thus on the anomalous couplings $\Delta\kappa_\gamma$ and $\lambda_\gamma$. In the following measurement this dependence is neglected. This leads to an additional systematic uncertainty which is estimated to be smaller than 5% of the measured cross-section.

## 3.1 Leptonic Final States

A distinct feature of the process $\mathrm{e^+e^-} \rightarrow \mathrm{e^+}\nu_\mathrm{e}\mathrm{W^-}$, $\mathrm{W^-} \rightarrow \ell^-\bar{\nu}_\ell$ is a high energy lepton from W decay with no other significant activity in the detector.

Events with one charged lepton (electron, muon or tau) with an energy of at least 15 GeV are selected. The lepton identification is based on the energy distribution in the electromagnetic and hadron calorimeters with respect to the trajectory of charged tracks. Events containing tracks that do not belong to the lepton are rejected. The visible energy, $\mathrm{E_{vis}}$, is calculated as the sum of the lepton energy, $\mathrm{E}_\ell$, and the energies of all neutral clusters in the event. The ratio $\mathrm{E}_\ell/\mathrm{E_{vis}}$ for events preselected as described above is shown in Figure 3a. The requirement $\mathrm{E}_\ell/\mathrm{E_{vis}} > 0.9$ suppresses background from two fermion production $\mathrm{e^+e^-} \rightarrow \ell^+\ell^-(\gamma)$. In addition, the energy in the 0.44 rad azimuthal angle sector along the missing energy direction must be below 1 GeV. For the single electron final states, the polar angle is required to be $|\cos\theta_\mathrm{e}| < 0.72$. This requirement reduces the contribution from Bhabha scattering and from the process $e^+e^- \to e^+e^-\nu\bar{\nu}$ where the $e^+e^-$ pair originates from a low-mass virtual photon.

A high energy lepton from the two fermion processes $e^+e^- \to \ell^+\ell^-(\gamma)$ which matches the above selection criteria is usually produced along with a high energy electron or photon detected in the forward-backward luminosity calorimeters. This correlation is a direct consequence of momentum conservation in the transverse plane. Therefore it is required that the energy deposition in the forward calorimeters, $E_{FB}$, does not exceed 15 GeV (Figure 3b). Two events satisfy all selection criteria: a 40.5 GeV electron candidate from the $\sqrt{s} = 161$ GeV data sample (shown in Figure 4) and a 28.5 GeV tau candidate from the $\sqrt{s} = 172$ GeV data sample.

The final lepton energy spectrum for the selected events is presented in Figure 5 together with the Monte Carlo expectations for the signal and background. The signal selection efficiencies at $\sqrt{s} = 161$ GeV are found to be (80±4)%, (55±2)% and (30±2)% for $W^- \to e^-\bar{\nu}_e$, $W^- \to \mu^-\bar{\nu}_\mu$ and $W^- \to \tau^-\bar{\nu}_\tau$ decays respectively. Each efficiency decrease slightly at $\sqrt{s} = 172$ GeV by approximately 4% absolute. The background in the $\sqrt{s} = 161$ GeV data sample is estimated to be $0.23 \pm 0.08$ events of which $0.11 \pm 0.01$ are from $e^+e^- \to \mu^+\mu^-(\gamma)$ and $e^+e^- \to \tau^+\tau^-(\gamma)$ events, $0.07 \pm 0.07$ are from $e^+e^- \to e^+e^-(\gamma)$ scattering and $0.05 \pm 0.03$ are from four-fermion processes. The background from two-photon interactions is found to be negligible. For the $\sqrt{s} = 172$ GeV data sample the background contamination is calculated to be $0.26 \pm 0.07$ events. The total error on the background is mostly due to the large uncertainty in the number of expected $e^+e^- \to e^+e^-(\gamma)$ events.

## 3.2 Hadronic Final States

The selection of candidates for the process $e^+e^- \to e^+\nu_e W^-$, $W^- \to q\,\bar{q}'$ is based on the following requirements: two acoplanar hadronic jets, no leptons, and large missing transverse energy.

High multiplicity hadronic events with more than four charged tracks are selected with large energy deposition in the electromagnetic calorimeter ($E_{ECAL} > 15$ GeV). All energy clusters in the event are combined to form two hadronic jets using the DURHAM algorithm [22]. The energy in the forward luminosity calorimeters is required to be smaller than 50 GeV. These cuts reduce contributions from the pure leptonic final states $e^+e^- \to e^+e^-(\gamma)$, $\mu^+\mu^-(\gamma)$, $\tau^+\tau^-(\gamma)$ and two-photon interactions $e^+e^- \to e^+e^-q\bar{q}$ while keeping a significant fraction of hadronic events from $e^+e^- \to Z(\gamma)$, $e^+e^- \to W^+W^-$ and $e^+e^- \to ZZ$.

To reject events from the two fermion production process $e^+e^- \to q\bar{q}(\gamma)$ the transverse missing energy is required to exceed 10 GeV. The missing momentum vector must be at least 0.30 rad away from the beam axis and the energy in the 0.44 rad sector along its direction must be below 10 GeV. In addition, the opening angle between the two jets in the plane perpendicular to the beam direction must not exceed 3.0 rad and the energy in the 0.70 rad sector along the direction opposite to the two jets must be below 15 GeV.

Events containing identified leptons with energy greater than 15 GeV are rejected in order to suppress the remaining background from $e^+e^- \to W^+W^-$ where one of the W bosons decays into leptons. In addition, three jets are formed for every remaining event using the DURHAM algorithm. The stereo angle defined by the directions of these jets is required to be smaller than 3.0 rad.

Four candidate events are selected in the $\sqrt{s} = 161$ GeV data sample and seven in the $\sqrt{s} = 172$ GeV data sample. A typical candidate event satisfying all selection criteria is shown in Figure 6. The jet-jet invariant mass spectrum of the selected candidates, $M_{inv}$, is shown in

Figure 7 together with the fitted signal and the Monte Carlo background predictions.

Events with invariant mass smaller than 100 GeV are used for the cross-section determination. This requirement rejects one candidate from the $\sqrt{s} = 172$ GeV data sample and reduces significantly the background contamination. The signal efficiency is then found to be $(41 \pm 2)\%$, independent of the centre of mass energy. The background is estimated to be $2.1 \pm 0.1$ events for the $\sqrt{s} = 161$ GeV data and $4.1 \pm 0.2$ events for the $\sqrt{s} = 172$ GeV data sample.

# 4 Results

The total cross-section of all signal processes is determined from a binned likelihood fit to the distributions presented in Figures 5 and 7. The background shapes and normalisations are fixed to the Monte Carlo prediction. The fitted signal cross-section, $\sigma(\mathrm{e^+e^-} \rightarrow \mathrm{e}\nu_\mathrm{e}\mathrm{W})$, corresponds to that of the process $\mathrm{e^+e^-} \rightarrow \mathrm{e}\nu_\mathrm{e}\mathrm{f}\,\bar{\mathrm{f}}'$, where $\mathrm{f}\,\bar{\mathrm{f}}'$ denotes a sum of $\ell\nu_\ell$ and $\mathrm{q}\,\bar{\mathrm{q}}'$ final states satisfying the phase space conditions (2). The measured values of the W branching fractions [23] are assumed in the fit. The relative contribution of the non-resonant $\mathrm{e}\nu_\mathrm{e}\mathrm{f}\,\bar{\mathrm{f}}'$ final states to the signal is fixed to the GRC4F prediction. The total cross-section is found to be

$$\sigma(\mathrm{e^+e^-} \rightarrow \mathrm{e}\nu_\mathrm{e}\mathrm{W}) = 0.61^{+0.43}_{-0.33} \pm 0.05 \text{ pb} \tag{3}$$

at $\sqrt{s} = 172$ GeV. The first error represents statistics and the second one accounts for the experimental systematics due to the uncertainties in the efficiency and the background contamination. The measured cross-section value is consistent with the Standard Model prediction of 0.35 pb calculated with GRC4F. This is the first experimental measurement of the process $\mathrm{e^+e^-} \rightarrow \mathrm{e^+}\nu_\mathrm{e}\mathrm{W^-}$.

The total cross-section for the leptonic final states (2) is measured to be

$$\sigma(\mathrm{e^+e^-} \rightarrow \mathrm{e}\nu_\mathrm{e}\ell\nu_\ell) = 0.17^{+0.20}_{-0.12} \pm 0.02 \text{ pb}$$

at $\sqrt{s} = 172$ GeV using the same fitting technique. The total cross-section for the hadronic final states (2) is found to be

$$\sigma(\mathrm{e^+e^-} \rightarrow \mathrm{e}\nu_\mathrm{e}\mathrm{q}\,\bar{\mathrm{q}}') = 0.45^{+0.41}_{-0.32} \pm 0.04 \text{ pb.}$$

The signal cross-section as a function of anomalous couplings is calculated with GRC4F. Using the same fitting technique as for the cross-section measurement, the following limits on $\Delta\kappa_\gamma$ and $\lambda_\gamma$ are obtained:

$$\begin{array}{rcccl} -3.6 & < & \lambda_\gamma & < & 3.6 \text{ at } 95\% \text{ CL.} \\ -3.6 & < & \Delta\kappa_\gamma & < & 1.5 \text{ at } 95\% \text{ CL.} \end{array} \tag{4}$$

The 63% and 95% contours are presented in Figure 8. These limits are comparable to similar limits on anomalous couplings reported at hadron colliders [4–6].

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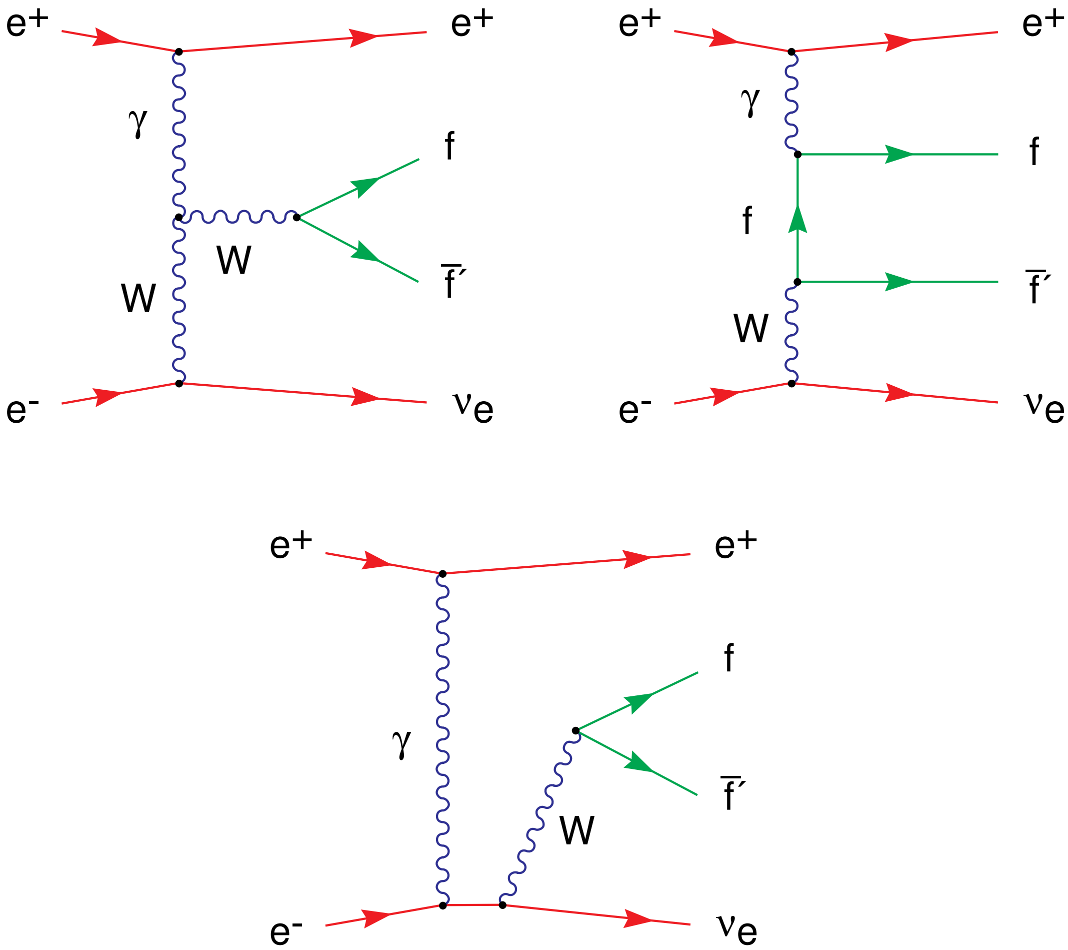


Figure 1: The dominant Feynman diagrams for the process (1).

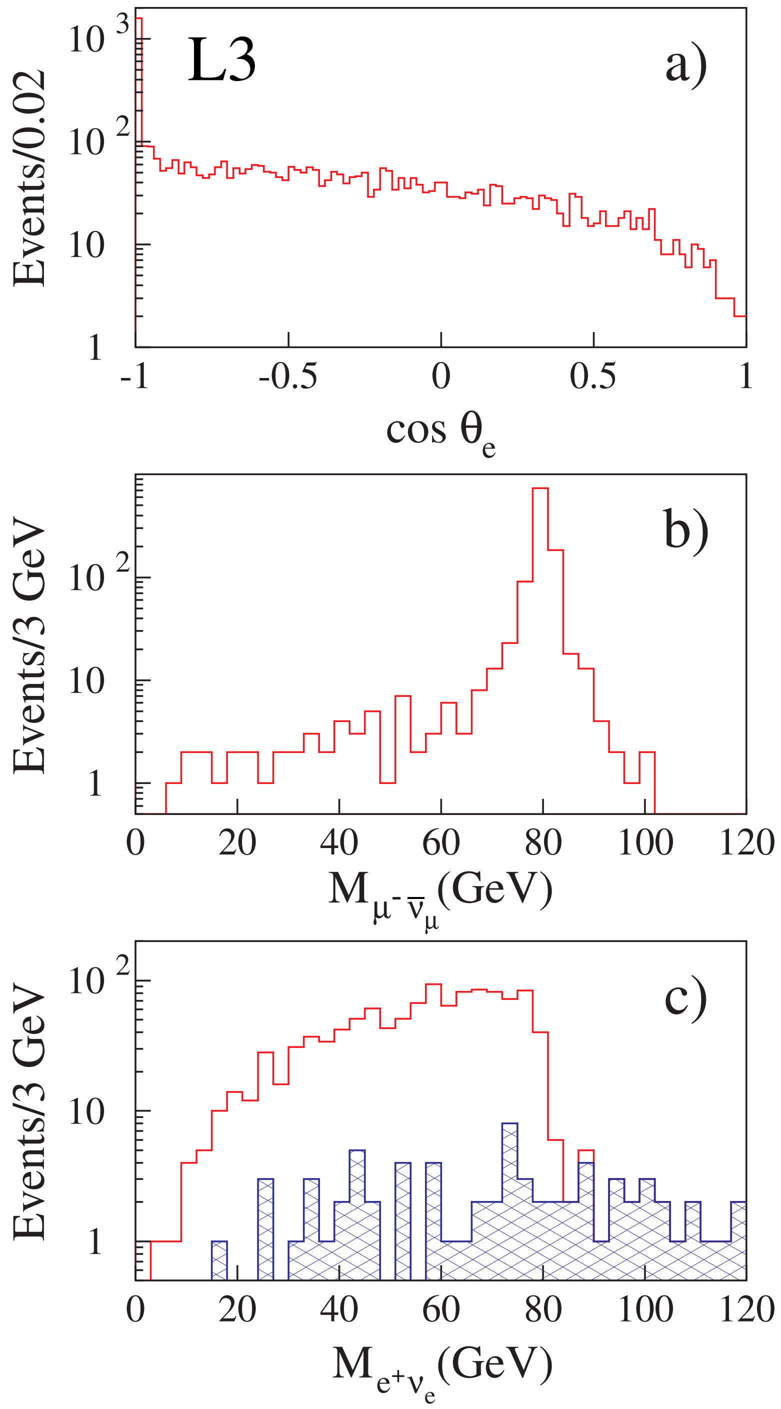


Figure 2: (a) The positron polar angle spectrum for all $e^+\nu_e\mu^-\bar{\nu}_\mu$ final states generated by GRC4F at $\sqrt{s} = 161$ GeV. The invariant mass spectrum of the $\mu^-\bar{\nu}_\mu$ (b) and $e^+\nu_e$ (c) pairs for the events satisfying phase space conditions (2). The hatched histogram in (c) represents events which meet the requirement $|M_{\mu\nu_\mu} - M_W| > 10$ GeV.

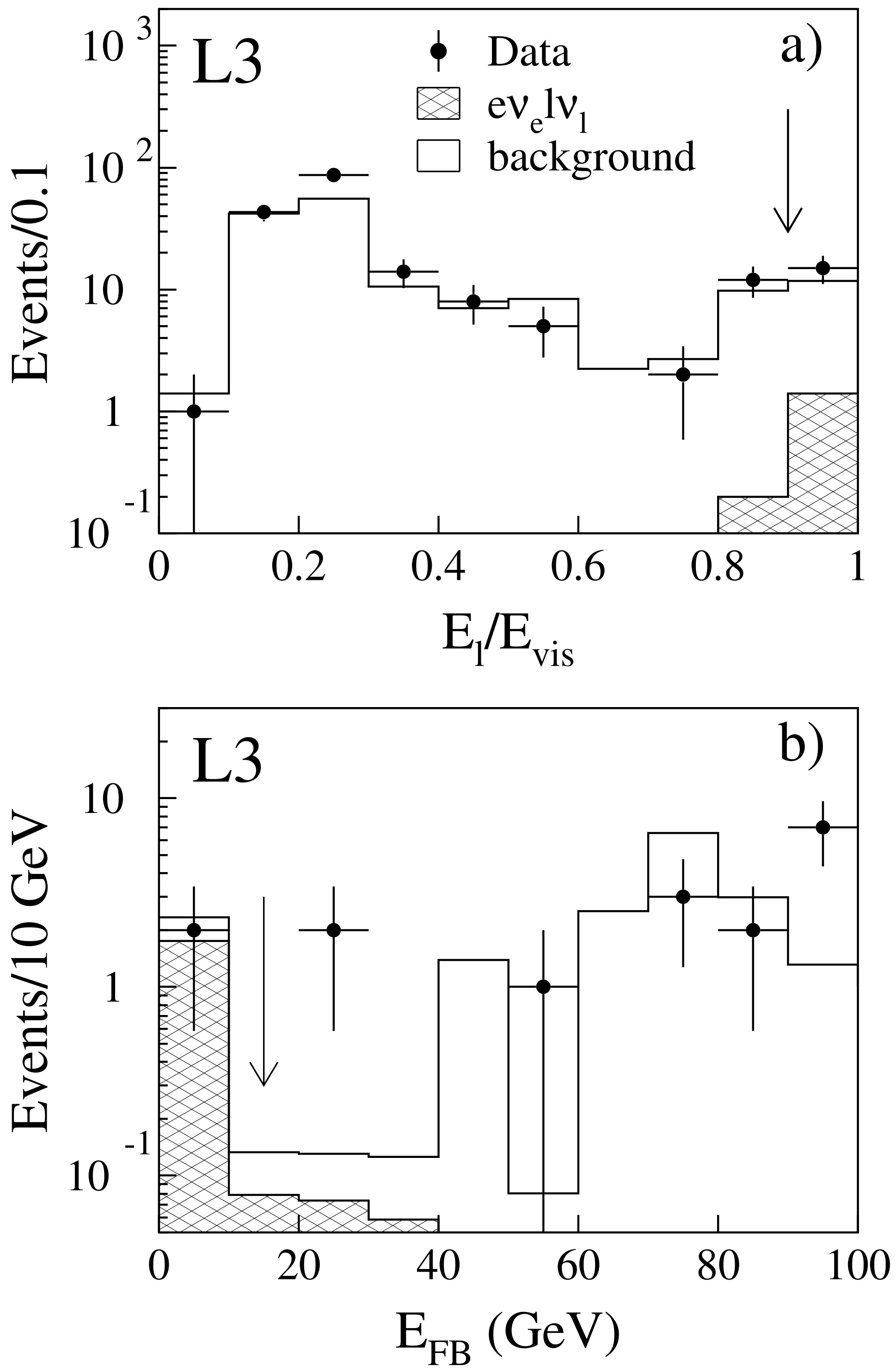


Figure 3: (a) The ratio $E_\ell/E_{vis}$ for the preselected single lepton data sample. (b) The spectrum of energy depositions in the forward-backward luminosity calorimeters for the events accepted by all other selection criteria. The hatched areas in (a) and (b) correspond to the contribution of $e^+\nu_e\ell^-\bar{\nu}_\ell$ final states. The arrows indicate the corresponding value of the applied cuts.

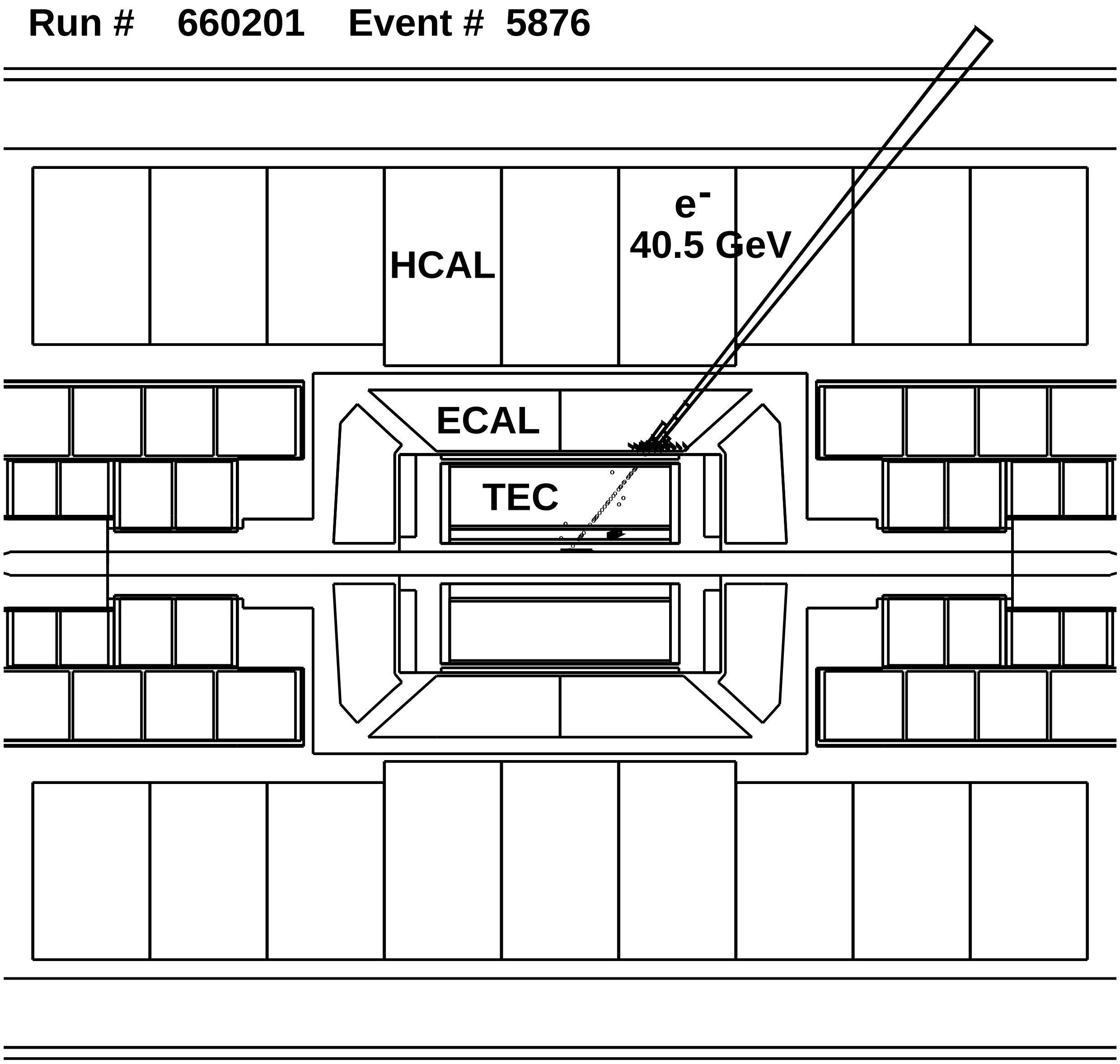


Figure 4: A $e^+e^- \rightarrow e^+\nu_e W^-$, $W^- \rightarrow e^-\bar{\nu}_e$ candidate event. In the upper hemisphere the 40.5 GeV electron is detected in the tracking chamber and in the electromagnetic calorimeter where the pulse heights represent the electron energy deposition . No significant energy deposition is observed in other subdetectors since the positron escapes in the beam pipe.

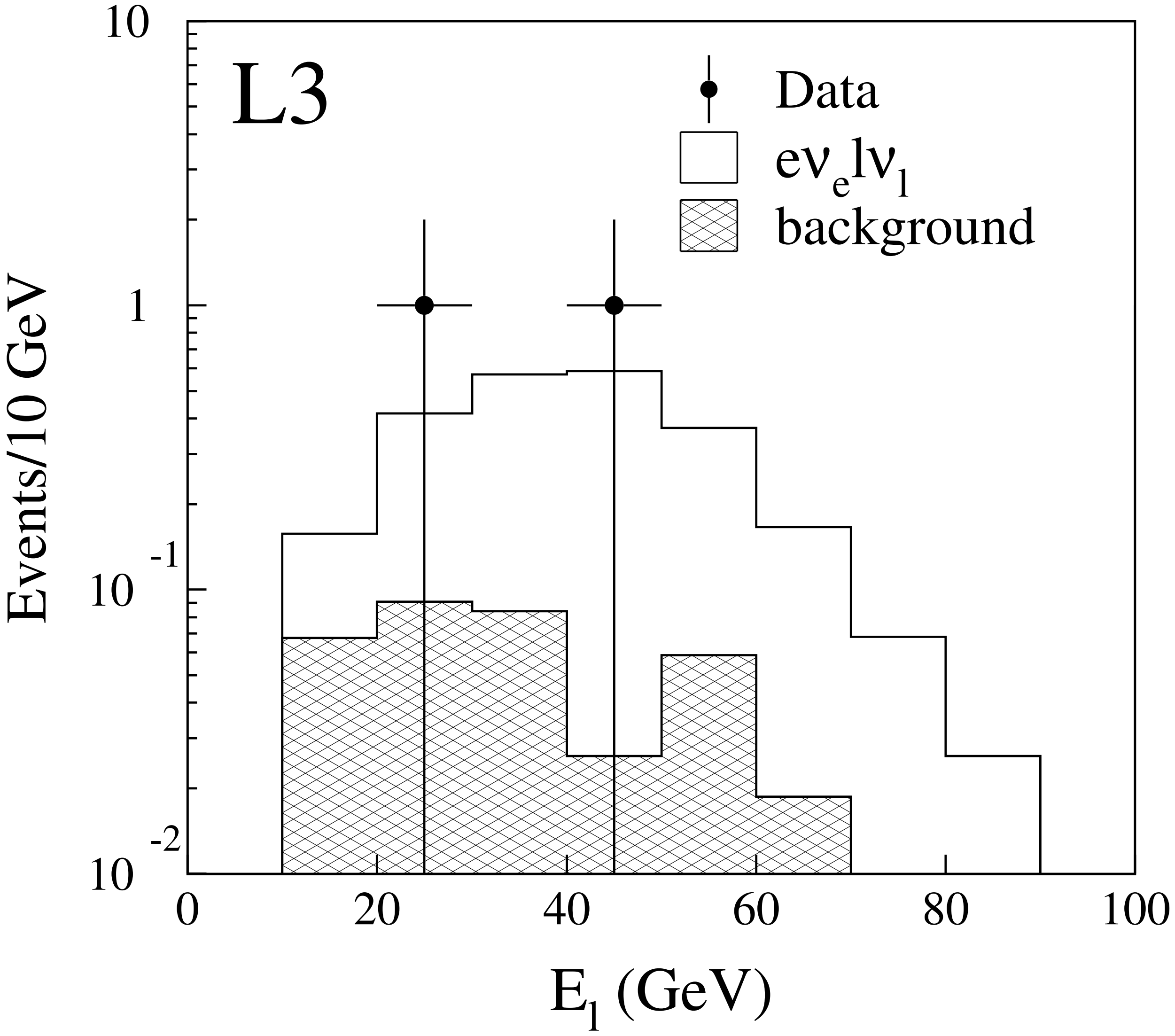


Figure 5: The energy spectrum of the selected leptonic candidates. The hatched histogram represents the background, the open histogram shows the fitted signal (2) from $e\nu_e\ell\nu_\ell$ final states.

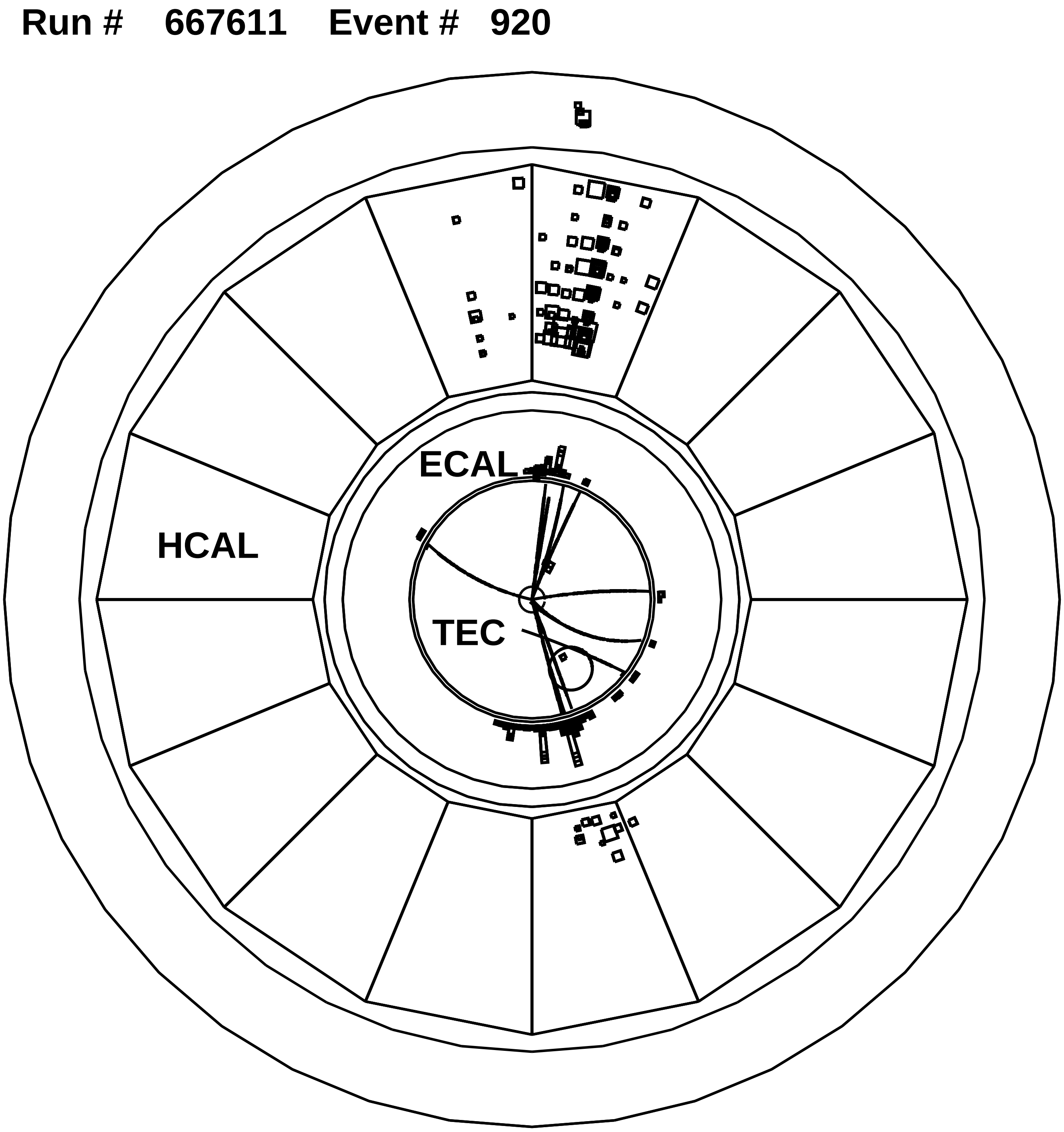


Figure 6: A candidate event for single W boson hadronic decay. The event consist of two acoplanar hadronic jets seen as groups of topologically connected tracks (TEC) and energy clusters (ECAL and HCAL). The pulse heights in the ECAL and size of squares in the HCAL are proportional to the energy deposition. The opening angle between the jets is 2.82 rad in the plane transverse to the beam direction. The jet-jet invariant mass is measured to be 91 GeV and the missing energy is 35 GeV in the transverse plane.

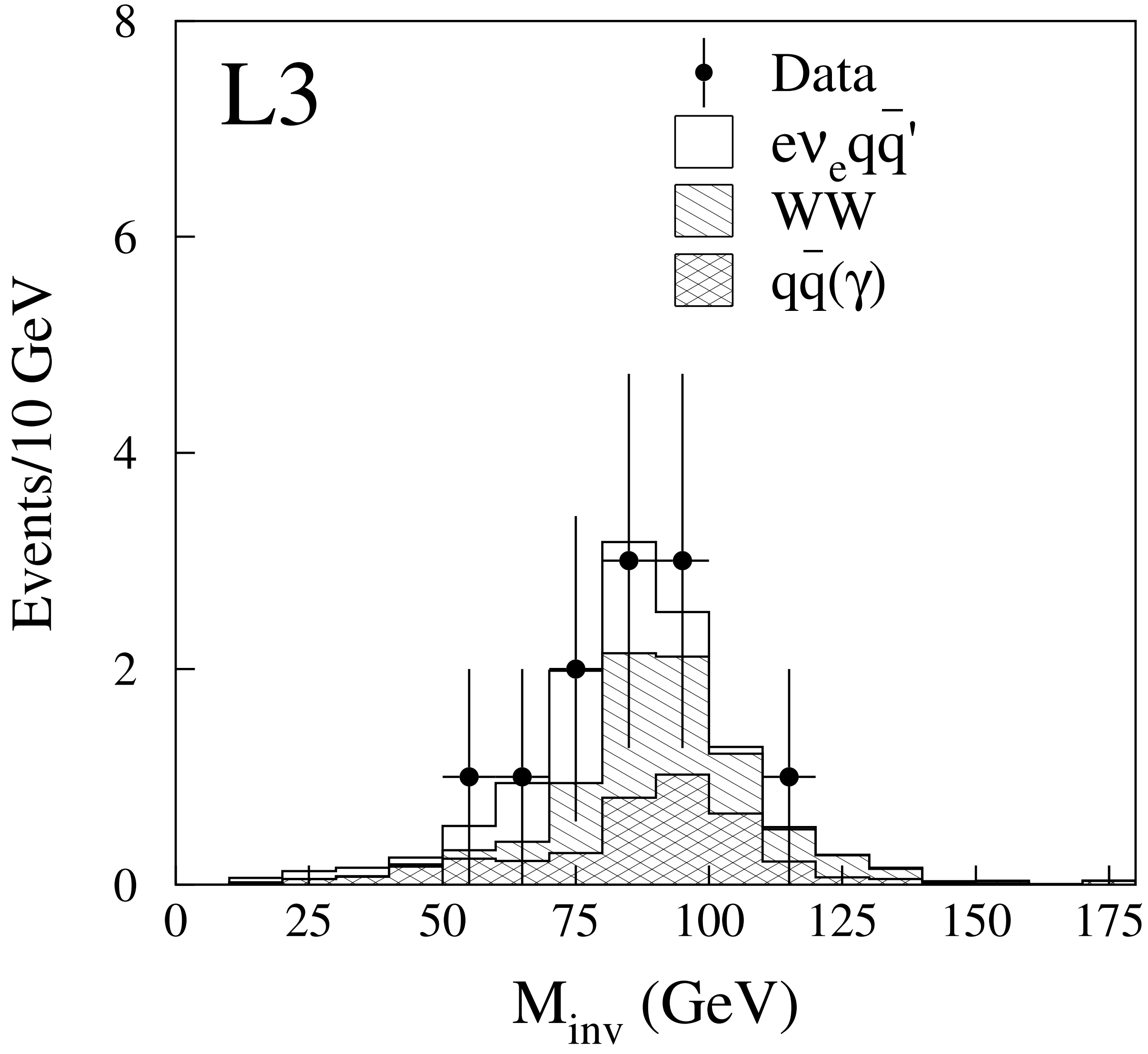


Figure 7: The jet-jet invariant mass spectrum, $M_{inv}$ of the selected hadronic candidates for the combined data sample. The hatched histogram represents the background, the open histogram shows the fitted signal from $e^+\nu_e q\,\bar{q}'$ final states.

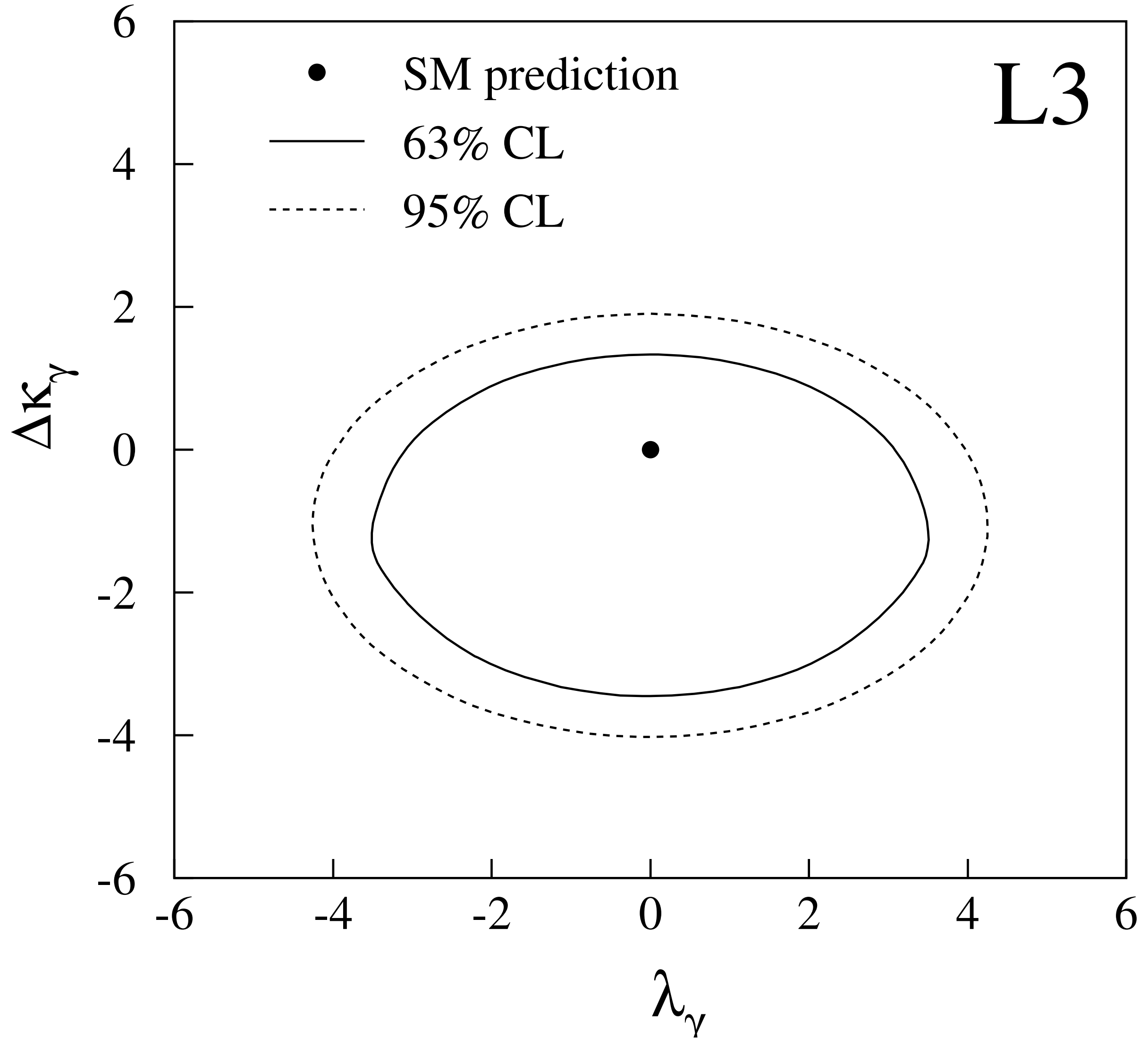


Figure 8: The contours corresponding to 63% and 95% confidence level exclusions in the $\Delta\kappa_\gamma - \lambda_\gamma$ plane.