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# Search for Anomalous ZZ$\gamma$ and Z$\gamma\gamma$ couplings in the process $e^+e^- \to Z\gamma$ at LEP

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## Abstract

We search for anomalous couplings in the ZZ$\gamma$ and Z$\gamma\gamma$ vertices using data collected with the L3 detector at LEP at centre–of–mass energies up to 208 GeV. No evidence of such couplings is found and preliminary limits are derived from the analysis of the process $e^+e^- \to Z\gamma$.

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# Introduction

The process $e^+e^- \to Z\gamma$ is interesting to test the existence of new physics [1]. In particular, the existence of anomalous couplings between neutral gauge bosons can be probed by means of this reaction. Effects coming from $ZZ\gamma$ and $Z\gamma\gamma$ couplings are expected to be very small in the Standard Model [1,2], but can be enhanced in compositeness models [3,4] or if new particles enter in higher order corrections.

Assuming only Lorentz and $U(1)_{em}$ gauge invariance, the most general form of the $ZZ\gamma$ and $Z\gamma\gamma$ vertices can be parametrized by means of eight anomalous couplings. The couplings are: $h_i^V$ ($i = 1$ to $4; V = \gamma, Z$), where a $V$ superscript corresponds to a $ZV\gamma$ vertex. The couplings $h_1^V$ and $h_2^V$ are CP violating whereas $h_3^V$ and $h_4^V$ are CP conserving. The anomalous couplings contribution to the $Z\gamma$ cross section increases with the centre–of–mass energy, $\sqrt{s}$, while the Standard Model contribution decreases. All these couplings are zero at tree level in the Standard Model, and only the CP conserving ones receive a small contribution ($\approx 10^{-4}$) at the one loop level [1,2]. An alternative parametrization, which introduces the energy scales of new physics $\Lambda_{iV}$ is [5]:

$$\frac{\sqrt{\alpha}\ h_i^V}{m_Z^2} \equiv \frac{1}{\Lambda_{iV}^2} \quad , i = 1,3 \tag{1}$$

$$\frac{\sqrt{\alpha}\ h_i^V}{m_Z^4} \equiv \frac{1}{\Lambda_{iV}^4} \quad , i = 2,4. \tag{2}$$

The anomalous couplings $h_i^V$ cannot get arbitrarily large values due to unitarity constraints, and should vanish when $s \to \infty$ [6,7]. For hadron colliders, this means that a form factor dependence should be used [7–10], because the effective centre–of–mass energy of the collision is variable. For $e^+e^-$ colliders, the centre–of–mass energy is fixed and no form factors are needed [11]. Therefore, the results are model independent and no hypothesis about the behaviour close to the new physics scale is made [11,12]. The main effects of anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings are an increase of the $Z\gamma$ total cross section and a modification of the differential spectrum of the photon, mainly at large polar angles. Limits on $ZZ\gamma$ and $Z\gamma\gamma$ couplings have been published at Tevatron [8–10] and LEP [13–15].

Data collected by the L3 detector [16] during 2000 at 200 GeV $\leq \sqrt{s} \leq$ 208 GeV amounting to a total luminosity of 217 pb$^{-1}$, are used to study the anomalous couplings $ZZ\gamma$ and $Z\gamma\gamma$ in the channel $e^+e^- \to q\bar{q}\gamma$.

# Event Selection

The main signature of the process $e^+e^- \to Z\gamma$ is the production of a photon of high energy, $E_\gamma$. A photon candidate is identified as a shower in the BGO electromagnetic barrel or end-cap calorimeters with more than 90% of its energy deposited in a $3 \times 3$ crystal matrix. The mass of the system recoiling against the photon, $m_{rec} = (s - 2E_\gamma\sqrt{s})^{1/2}$, is required to satisfy 80 GeV $< m_{rec} <$ 110 GeV, and thus is consistent with that of a Z. For the $\sqrt{s}$ values considered, the cuts on the recoiling mass correspond to an energy of the photon between 73 GeV and 89 GeV.

In the estimation of signal and background processes the following Monte Carlo generators have been used: KK2F [17] for $e^+e^- \to q\bar{q}\gamma(\gamma)$, EXCALIBUR [18] for four fermion final states

| Process | $\sqrt{s}$ (GeV) | $\mathcal{L}$ (pb$^{-1}$) | $\epsilon$ (%) | Events | $\sigma$ (pb) | $\sigma_{\rm SM}$ (pb) |
|---|---|---|---|---|---|---|
| $e^+e^- \to q\bar{q}\gamma$ | 205.5 | 78.94 | 25.0 $\pm$ 0.1 | 342 | 16.42 $\pm$ 0.97 | 16.34 |
| | 206.6 | 130.03 | 25.2 $\pm$ 0.1 | 518 | 14.98 $\pm$ 0.70 | 16.06 |
| | 208.0 | 8.297 | 24.8 $\pm$ 0.1 | 35 | 16.11 $\pm$ 2.99 | 15.62 |

Table 1: The centre–of–mass energies, integrated luminosities, $\mathcal{L}$, and acceptances, $\epsilon$, of the selection, the number of selected events and measured cross sections (background subtracted). The error on the acceptances includes Monte Carlo statistics. The corresponding Standard Model cross sections $\sigma_{\rm SM}$ [17] are also listed.

and PHOJET [19] for two virtual photon collisions. All generated events are passed through a simulation of the L3 detector response [20] and through the same analysis procedure used for data. Time dependent inefficiencies are taken into account in the simulation procedure.

Cross sections and acceptances are quoted within the following phase space cuts: at least one photon of energy greater than 20 GeV with polar angle in the range $5^\circ < \theta_\gamma < 175^\circ$.

### Selection of $e^+e^- \to q\bar{q}\gamma$ events

In addition to a photon candidate recoiling against a Z, high multiplicity and energy-momentum balance are required to select $e^+e^- \to q\bar{q}\gamma$ events:

- The event must have more than 6 tracks and more than 11 calorimetric clusters.
- The transverse energy imbalance must be less than 15% of the visible energy, and the longitudinal energy imbalance less than 20% of the visible energy.
- Events are rejected if the photon candidate has an associated track and $|\cos\theta_\gamma| < 0.85$.
- The polar angle of the photon, $\theta_\gamma$, must be in the range $|\cos\theta_\gamma| < 0.97$.

The trigger inefficiency is estimated to be negligible due to the redundancy of subtriggers involved in triggering this final state. Two backgrounds are found to contribute: $e^+e^- \to q\bar{q}'e\nu$ and $e^+e^- \to q\bar{q}e^+e^-$, where one of the electrons fakes a photon, giving 2.2% and 2.5% contamination respectively.

The measured cross sections for $e^+e^- \to q\bar{q}\gamma$, once the background is subtracted, are shown in Table 1 and are in agreement with the Standard Model expectations. The evolution of the cross-section $\sigma(e^+e^- \to q\bar{q}\gamma(\gamma))$ with $\sqrt{s}$, as obtained from L3 data recorded during the last years, is presented in Figure 1. Figures 2 and 3 show the recoiling mass distribution, the polar angle of the photon and the invariant mass of the $q\bar{q}$ system.

# Results

The analysis is performed by means of the "Optimal Variables" [21] approach. The differential cross section of the process $e^+e^- \to Z\gamma$ is written as a function of the anomalous couplings:

$$\frac{d\sigma}{d\vec{\Omega}} = c_0(\vec{\Omega}) + \sum_{i=1}^{4}\sum_{V=\gamma,Z} c_{1,i,V}(\vec{\Omega})h_i^V + \sum_{i=1}^{4}\sum_{V=\gamma,Z}\sum_{j=1}^{4}\sum_{V'=\gamma,Z} c_{2,ij,V,V'}(\vec{\Omega})h_i^V h_j^{V'}, \qquad (3)$$

where $\vec{\Omega} = (E_\gamma, \theta_\gamma, \phi_\gamma, \theta_f^{\rm Z}, \phi_f^{\rm Z})$. $E_\gamma, \theta_\gamma$ and $\phi_\gamma$ are the energy and angular variables of the photon, and $\theta_f^{\rm Z}, \phi_f^{\rm Z}$ the angles of the fermion $f$ in the Z rest frame. As the couplings are small, the quadratic term is neglected, and the optimal variable for each coupling is defined as:

$$\mathcal{O}_{1,i,V} \equiv \frac{c_{1,i,V}(\vec{\Omega})}{c_0(\vec{\Omega})}. \quad (4)$$

This method profits from having a one-dimensional parametrization which uses all the available kinematic information.

A binned maximum likelihood fit of the expected optimal variable distribution to the data is performed. A reweighting technique is used to compute the expected number of events in the presence of anomalous couplings. In these fits, only one coupling is fitted each time, keeping all the other couplings at zero. The distributions of the optimal variables for the couplings $h_1^{\rm Z}$ and $h_4^\gamma$ are shown as an example in Figures 4 and 5, respectively.

No deviations from the Standard Model expectations are found. The limits on the anomalous couplings at 95% confidence level (CL) are:

$$\begin{array}{ll} -0.22 < h_1^{\rm Z} < 0.23 & -0.06 < h_1^\gamma < 0.11 \\ -0.12 < h_2^{\rm Z} < 0.11 & -0.08 < h_2^\gamma < 0.02 \\ -0.31 < h_3^{\rm Z} < 0.25 & -0.05 < h_3^\gamma < 0.05 \\ -0.13 < h_4^{\rm Z} < 0.19 & -0.02 < h_4^\gamma < 0.04. \end{array}$$

Combining the statistics available since 1998, that is data taken at $\sqrt{s}$ between 189 GeV and 208 GeV and comprising a total luminosity of 620 pb$^{-1}$, the following, more restringent, limits at 95% CL are obtained for the anomalous couplings:

$$\begin{array}{ll} -0.17 < h_1^{\rm Z} < 0.15 & -0.06 < h_1^\gamma < 0.05 \\ -0.10 < h_2^{\rm Z} < 0.09 & -0.05 < h_2^\gamma < 0.02 \\ -0.23 < h_3^{\rm Z} < 0.11 & -0.05 < h_3^\gamma < 0.00 \\ -0.07 < h_4^{\rm Z} < 0.15 & -0.00 < h_4^\gamma < 0.04. \end{array}$$

Fits to the two-dimensional distributions of the optimal observables are performed to determine the pairs of the CP-violating and CP-conserving couplings, keeping in each case the other couplings fixed at zero. Results at 95% CL are shown in Figures 6 and 7, where contours for data from 1998 and 1999 together, as well as the combination of all statistics (1998 to 2000) is shown, for comparison.

The main sources of systematic errors are considered. The influence of the angular resolution for jets and photons is found to be negligible. The systematic error due to the limited Monte Carlo statistics is computed to be 0.01 for limits on individual couplings and 0.02 for two-dimensional limits. The systematic uncertainty coming from the Monte Carlo modeling of detector inefficiencies and the resolution in the photon energy is estimated to be below 0.02. These effects are included in the limits presented.

If the data are interpreted in terms of new physics scales using formulae (1) and (2), the following limits (95% CL) to the new physics scales are obtained, using the 2000 sample:

$$\begin{array}{ll} \Lambda_{1{\rm Z}} > \ 589 \text{ GeV} & \Lambda_{1\gamma} > 946 \text{ GeV} \\ \Lambda_{2{\rm Z}} > \ 288 \text{ GeV} & \Lambda_{2\gamma} > \ 389 \text{ GeV} \\ \Lambda_{3{\rm Z}} > \ 576 \text{ GeV} & \Lambda_{3\gamma} > 1414 \text{ GeV} \\ \Lambda_{4{\rm Z}} > \ 274 \text{ GeV} & \Lambda_{4\gamma} > \ 390 \text{ GeV}. \end{array}$$

To determine the confidence levels the probability distributions are normalized over the physically allowed range of the parameters, ($\Lambda > 0$).

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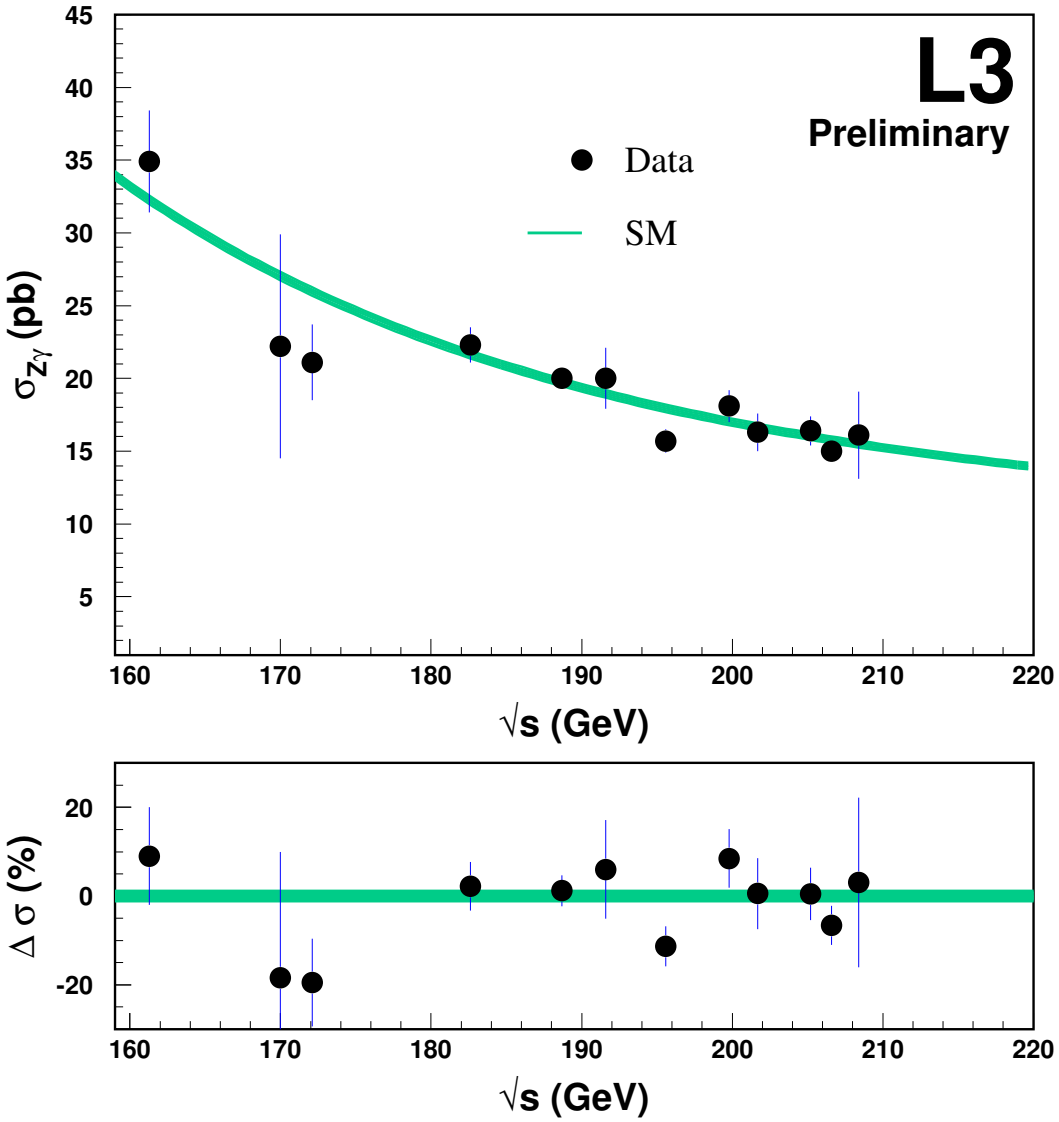


Figure 1: Evolution of the cross-section $\sigma(e^+e^- \to q\bar{q}\gamma(\gamma))$ with $\sqrt{s}$, obtained from L3 data recorded at 161 GeV $\leq \sqrt{s} \leq$ 208 GeV. Data are represented by the dots, while the solid line gives the evolution predicted by the SM, with a 1% uncertainty in the cross-section.

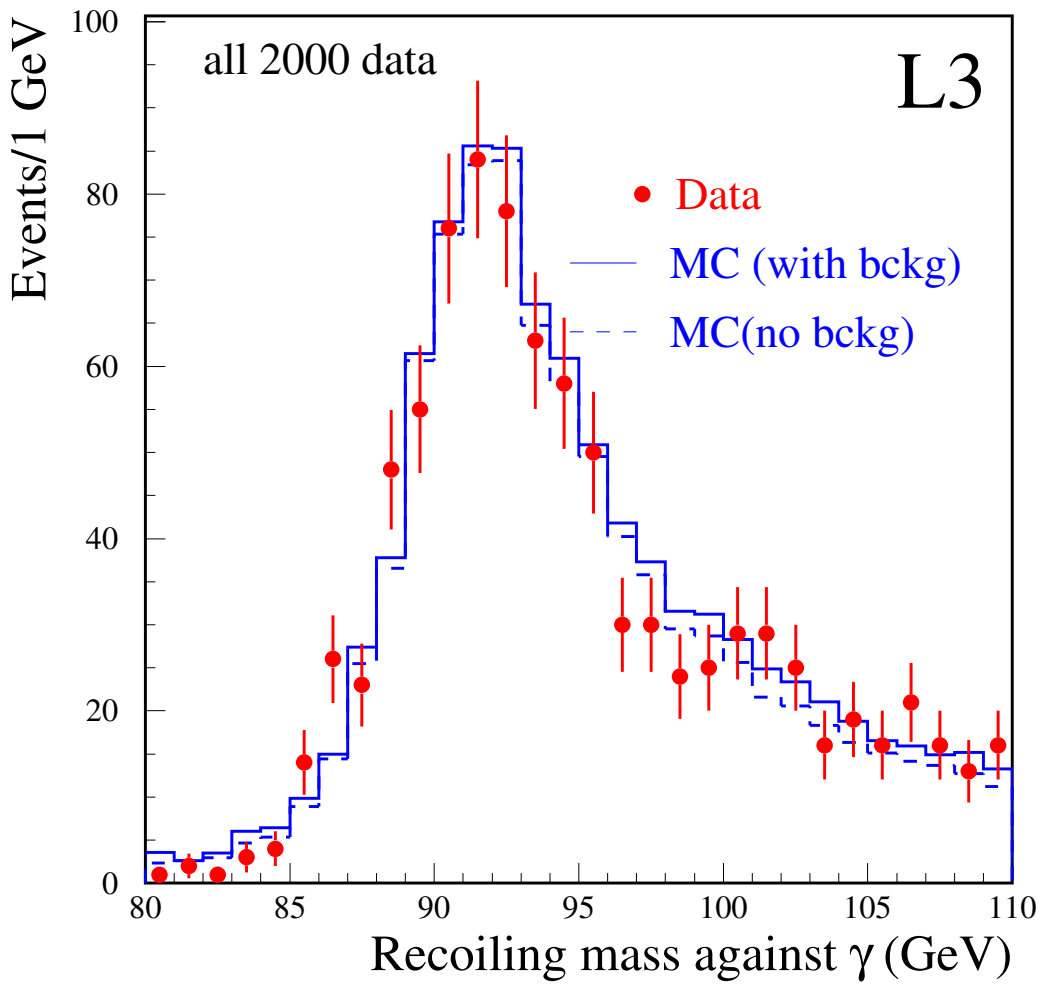


Figure 2: Distribution of the mass recoiling to the photon candidate in $e^+e^- \to q\bar{q}\gamma$ events. The points are data and the histogram is the Standard Model Monte Carlo prediction.

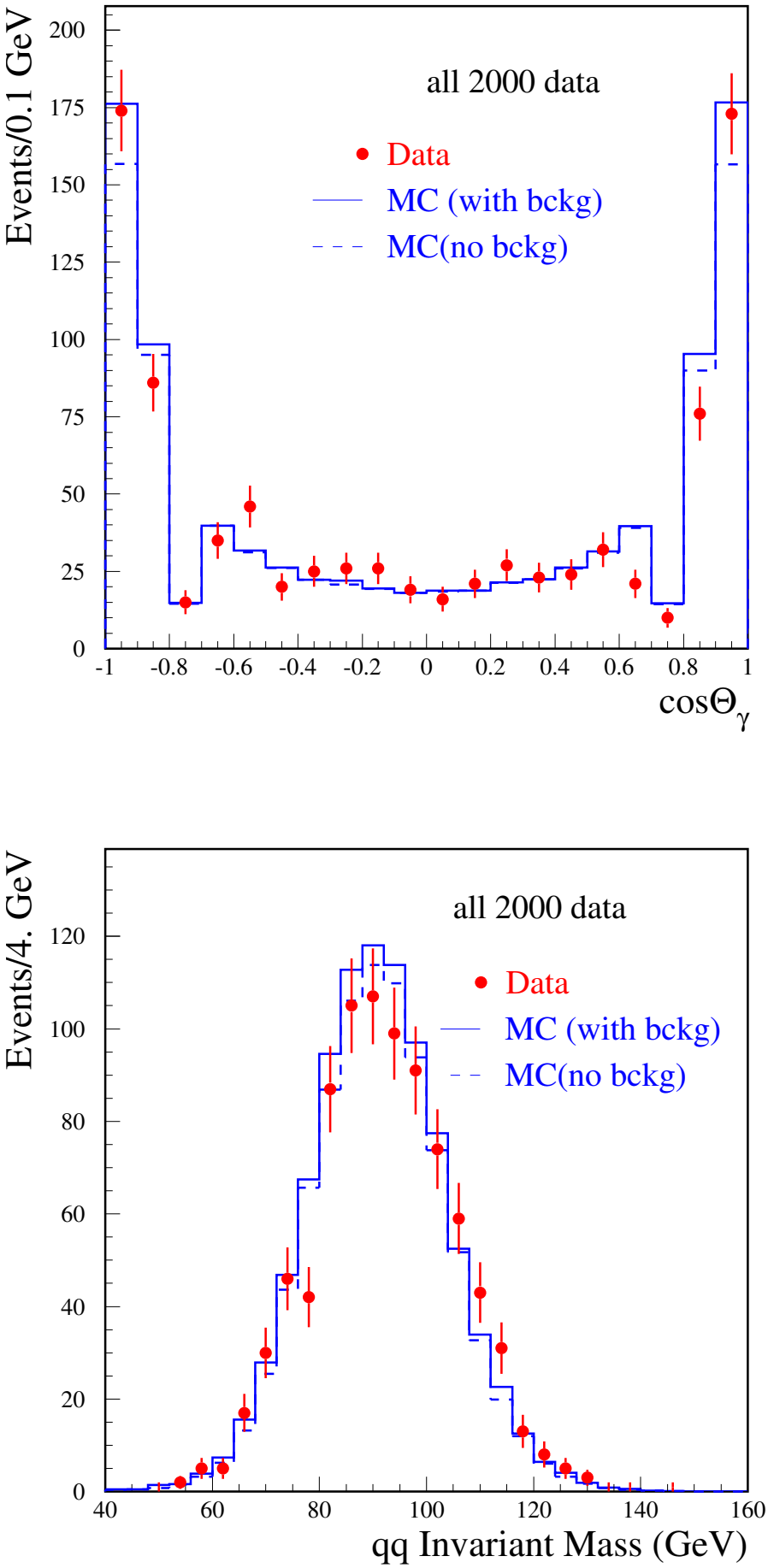


Figure 3: Polar angle of the photon and invariant mass of the $q\bar{q}$ system distributions in $e^+e^- \to q\bar{q}\gamma$ events. The points are data and the histogram is the Standard Model Monte Carlo prediction.

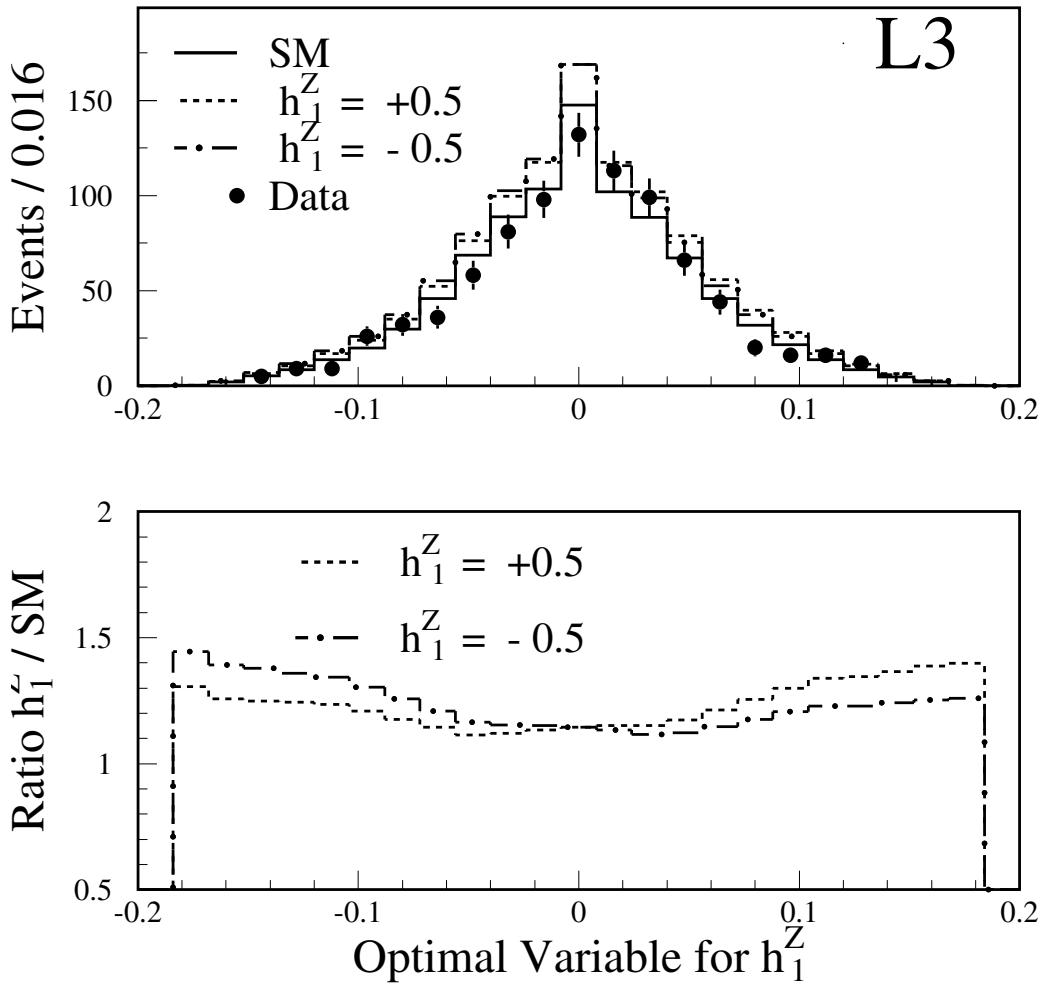


Figure 4: Distribution of the optimal variable for the CP violating coupling $h_1^Z$. Data are shown, together with the expectations for the Standard Model (SM) and for anomalous couplings, $h_1^Z = \pm 0.5$. In the lower plot the ratio between the anomalous couplings contribution, $h_1^Z = \pm 0.5$, and the SM expectation is presented.

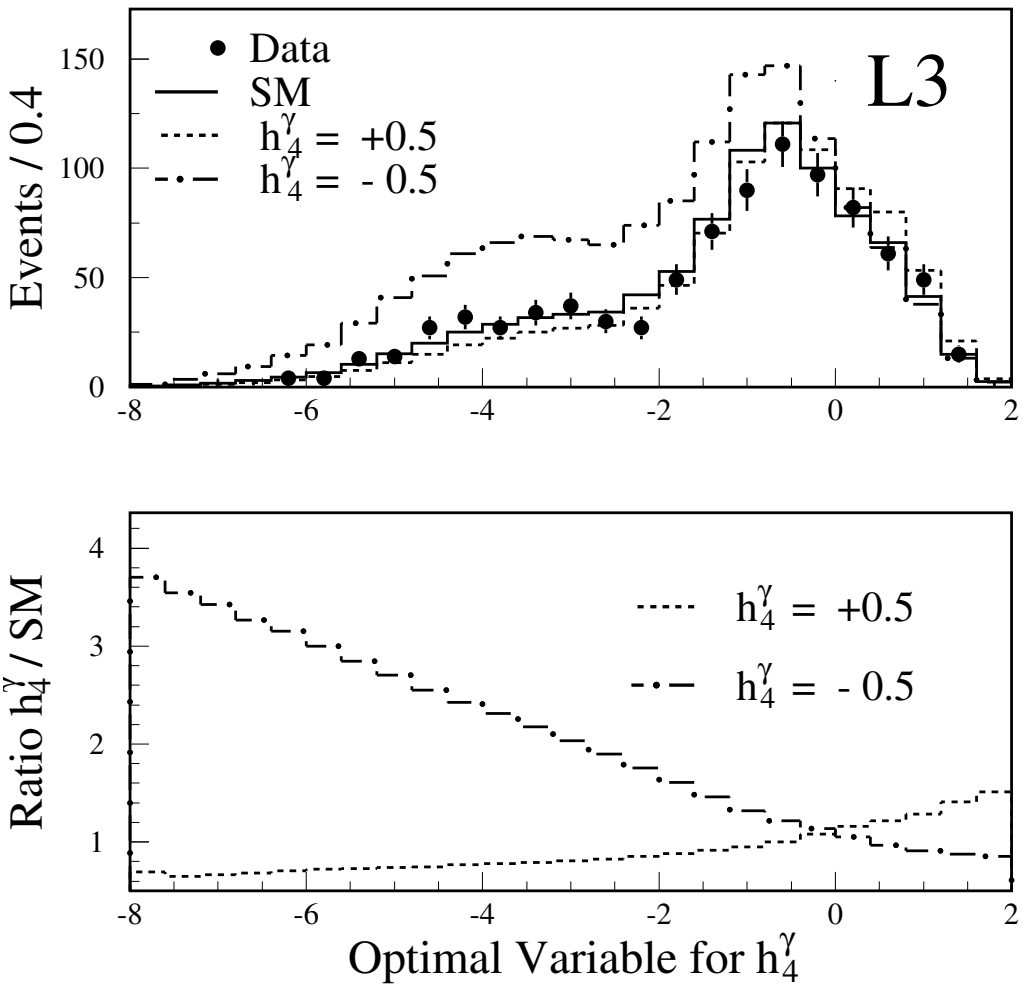


Figure 5: Distribution of the optimal variable for the CP conserving coupling $h_4^\gamma$. Data are shown, together with the expectations for the Standard Model (SM) and for anomalous couplings, $h_4^\gamma = \pm 0.5$. In the lower plot the ratio between the anomalous couplings contribution, $h_4^\gamma = \pm 0.5$, and the SM expectation is presented.

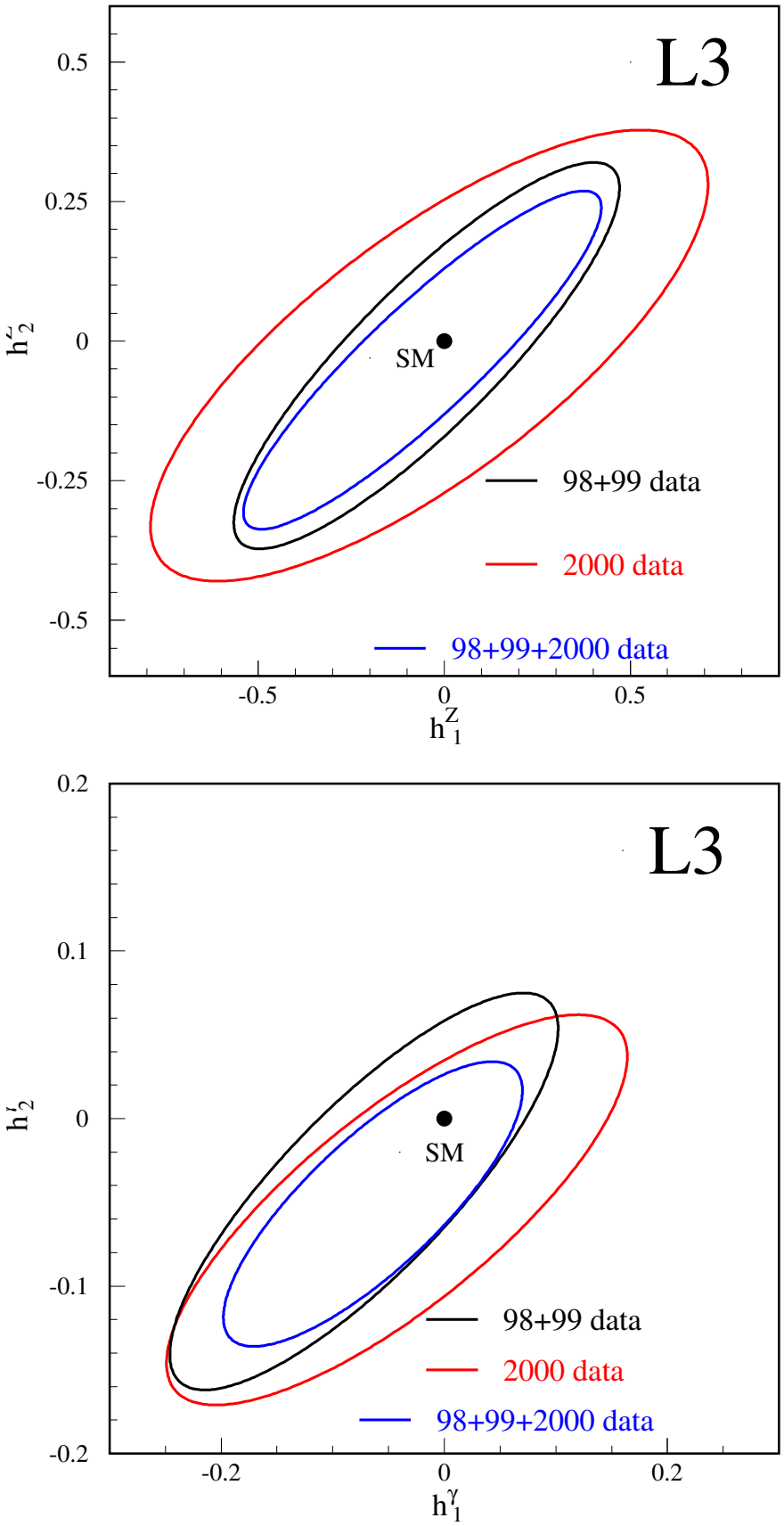


Figure 6: Limits at 95% CL on the CP-violating coupling parameters, $h_2^Z$ versus $h_1^Z$ and $h_2^\gamma$ versus $h_1^\gamma$. The Standard Model predictions are indicated by the points. The regions outside the contours are excluded. Results are presented using 1998 [13] and 1999 data samples.

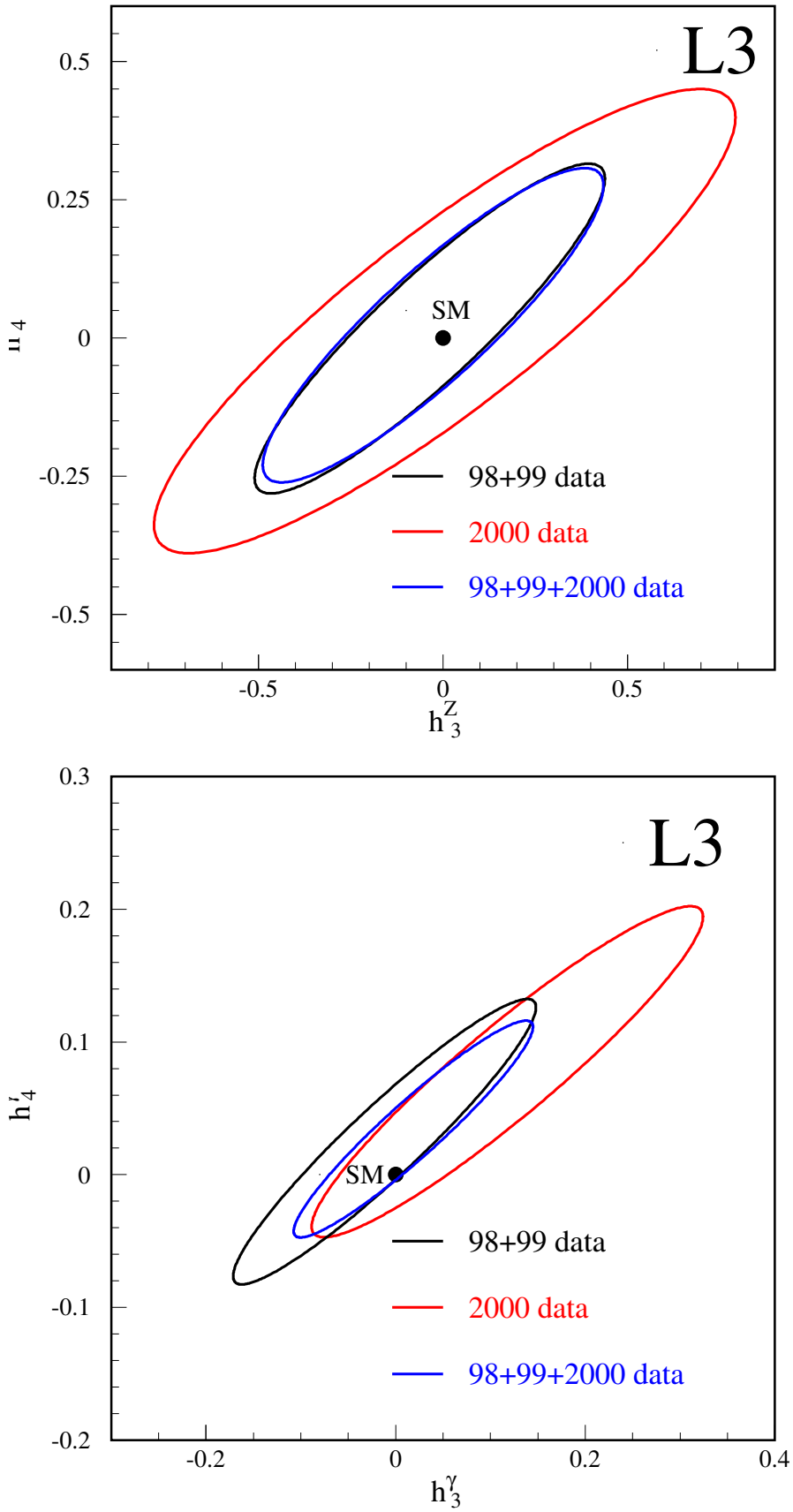


Figure 7: Limits at 95% CL on the CP-conserving coupling parameters, $h_4^Z$ versus $h_3^Z$ and $h_4^\gamma$ versus $h_3^\gamma$. The Standard Model predictions are indicated by the points. The regions outside the contours are excluded. Results are presented using 1998 [13] and 1999 data samples.