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Search for new physics in energetic single photon production in e^+e^- annihilation at the Z resonance

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Abstract

Using a sample of e^+e^- annihilation events collected with the L3 detector at the Z resonance corresponding to an integrated luminosity of 137 pb^{-1}, we have searched for anomalous production of γX final states where X represents stable, weakly interacting particles and the photon energy is greater than 15 GeV. The sample of events found is consistent with Standard Model expectations. Upper limits are set on Zγ couplings, the τ neutrino magnetic moment, and the branching ratio for Z $\rightarrow \gamma$X.

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Introduction

Production of single–photon events in e^+e^- annihilation at the Z resonance is sensitive to new physics. Processes contributing to the invisible width $\Gamma_{\rm inv}$ of the Z may be detected by counting single–photon events which arise from Z decay into stable, weakly interacting particles accompanied by a photon from initial–state radiation [1–3]. Near the Z resonance, photon energies associated with initial–state radiation are predominantly less than a few GeV. Single–photon events, in which the photon couples directly to the Z or is produced by a radiative transition in the final state, are also expected from substructure in the gauge boson [4–7] or lepton sectors [9], supersymmetry [10,11], and other new physics scenarios [12,13]. In contrast to Z decay into invisible particles accompanied by a photon from initial–state radiation, the energy carried by these photons is typically a significant fraction of the beam energy. Moreover, the distribution of these photons in polar angle is not as forward–backward–peaked as that of photons from initial–state radiation.

We have carried out a search for new physics manifest as a direct coupling between the photon and the Z or a radiative transition in the final state by studying energetic single photon events ($E_\gamma > 15$ GeV) in the data collected with the L3 detector [14] at LEP corresponding to an integrated luminosity of 137 $\rm pb^{-1}$. The number of hadronic Z decays to which this sample corresponds is 3.3×10^6. The energetic single–photon candidates are described in terms of their distributions in energy and polar angle and compared with expectations from Standard Model processes. We find the data and the Standard Model to be in good agreement. These results are then used to set limits on $Z\gamma$ couplings and the τ neutrino magnetic moment [15] and on the branching ratio for $Z \rightarrow \gamma X$ where X refers to stable, weakly interacting particles.

Event Selection

The L3 detector triggered on energetic single–photon events using the logical OR combination of the BGO electromagnetic energy triggers, described in detail in [16].

The experimental signature is an energetic, electromagnetic shower and an otherwise "empty" detector as defined below. In addition to possible new physics processes, events with this signature can occur due to (a) neutrino pair production accompanied by initial–state radiation, (b) QED events, e.g. $e^+e^- \rightarrow e^+e^-\gamma(\gamma)$, in which all final–state particles but the photon are outside the active volume of the detector, and (c) out–of–time cosmics. The number of events from process (a) can be reduced by taking advantage of the fact that initial–state radiation tends to be emitted along the beam direction and/or has energy which is typically of the order of Γ_Z. Events from process (b) can be eliminated by requiring the photon energy and production angle to be large enough so that by momentum conservation at least one other final–state particle is well within the active detector volume. Applying cuts on the shape of the shower is effective for reducing the contribution from cosmics. In order to suppress contributions from processes (a)–(c) while retaining good acceptance, the following requirements were applied to the most energetic cluster found in the electromagnetic calorimeter:

- Its energy must be greater than 15 GeV and its polar angle must lie in the range $20^\circ < \theta < 34.5^\circ$, $44.5^\circ < \theta < 135.5^\circ$, or $145.5^\circ < \theta < 160^\circ$.

- The transverse shape of the cluster must be consistent with a photon originating from the interaction point.

Apart from the energetic electromagnetic cluster selected by the above cuts, the detector was required to be "empty" as defined by the following criteria. There are no additional clusters present in the electromagnetic calorimeter with the deposit in the most energetic crystal exceeding approximately 100 MeV. The energy detected in the other calorimeters is attributable to noise or shower leakage from the electromagnetic calorimeter. There are no tracks in the central tracking chamber or the muon chamber. Any scintillator hit either lies directly behind the most energetic electromagnetic cluster and is in time with the beam crossing or is consistent with random noise. The "empty" detector cuts rejected beam–gas interactions, hadronic and charged leptonic decays of the Z, and QED events with two or more final–state particles within the acceptance. Cosmics were further suppressed by the cuts involving the scintillator counters and muon chambers.

We evaluated the selection efficiency using detector–simulated $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$ events, random trigger events, and large–angle $e^+e^- \rightarrow e^+e^-$ events. The trigger efficiency was measured by simulation following a procedure similar to the one used to measure our trigger efficiency for low–energy single–photon events [2]. The average trigger and selection efficiency combined was found to be 82% for simulated $\nu\bar{\nu}\gamma(\gamma)$ events passing the fiducial cuts on energy and angle listed above for the most energetic deposit in the electromagnetic calorimeter. The efficiency is independent of photon energy for the range of interest and is constant to within $\pm 5\%$ in polar angle.

A total of 14 events were found by our selection. The distributions of the photon energy and the cosine of its polar angle are shown in Figure 1. Also shown are the Standard Model expectations from production of neutrino pairs accompanied by initial–state radiation, radiative Bhabha events, and $e^+e^- \rightarrow \gamma\gamma(\gamma)$. The contribution from cosmics is negligible. The $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$ events were generated with the NNGSTR program [17], the TEEG program [18] was used to generate $e^+e^- \rightarrow e^+e^-\gamma$ events, and $e^+e^- \rightarrow \gamma\gamma(\gamma)$ events were generated using a modified version of the program based on [19]. The response of the L3 detector to the generated events was modelled using the GEANT library [20]. The simulated data were subjected to the same reconstruction and event selection as the real data.

The observed distributions are consistent with Standard Model predictions. The total number of events expected from the Standard Model is 14.1. If one instead requires that the photon energy be greater than half the beam energy, 2 events are selected from the data and 2.4 events are expected from the Standard Model in the $\nu\bar{\nu}\gamma$ channel.

Limits on new physics

We present limits on $ZZ\gamma$ couplings, the τ neutrino magnetic moment, and the branching ratio for $Z \rightarrow \gamma X$. The upper limit on $BR(Z \rightarrow \gamma X)$ may be recast as a limit on any process mediated by on–shell Z exchange and resulting in an energetic single photon final state.

The total uncertainty arising from finite Monte Carlo statistics, the method used to measure the trigger efficiency, and other sources was estimated to be 6%; it was taken into account in the limit calculations. In the case of one free parameter, the number of events expected from new physics was determined as a function of the parameter, and then the upper limit on the parameter was calculated from the limit on the number of excess events statistically allowed by the data. Poisson statistics were assumed for the observed number of events and the expected Standard Model background. For calculating the limits in the case of two free parameters, a maximum likelihood fit to the number of observed events was carried out. The two–dimensional limit contours at the 95% C.L. correspond to a log likelihood 3 units below the maximum. The effect of initial state radiation on cross sections was taken into account. Unless otherwise stated, interference between Standard Model and new physics amplitudes was neglected.

ZZγ Couplings

Self–couplings of the electroweak gauge bosons are a prominent feature of the Standard Model, and several extensions have been proposed [4, 7, 8] which imply couplings also between the neutral gauge bosons. Taking the ZZγ coupling in particular, the most general vertex function invariant under Lorentz and electromagnetic gauge transformations can be described in terms of four independent dimensionless form factors, denoted by h_i^{Z}, $i = 1, 2, 3, 4$. The contributions involving h_1^{Z} and h_2^{Z} are CP–violating while those involving the other pair of form factors are CP–conserving. All four form factors are zero at the tree level in the Standard Model. At the one–loop level, h_1^{Z} and h_2^{Z} are zero while the CP–conserving form factors are nonzero but too small to be seen. Thus observation of ZZγ couplings would be a clear signal of physics beyond the Standard Model.

The single–photon topology from ZZγ couplings is obtained in the case that the photon is real and the final–state Z decays into neutrinos. ZZγ couplings would be manifest in the photon energy spectrum as an enhancement which becomes visible at $E_\gamma \sim 15$ GeV and increases monotonically with energy until near the kinematic limit. This is illustrated by the dotted histogram in Figure 2 where we have taken just one of the form factors describing the $ZZ\gamma$ vertex to be nonzero. We have followed [6] in adopting the parameterization $h_i^{\mathrm{Z}} = h_{i0}^{\mathrm{Z}}/(1 + s/\Lambda_{\mathrm{Z}}^2)^{\mathrm{n}_i}$ with $\mathrm{n}_1 = \mathrm{n}_3 = 3$ and $\mathrm{n}_2 = \mathrm{n}_4 = 4$; $\Lambda_{\mathrm{Z}} = 500$ GeV was used for the calculation shown in Figure 2.

In order to calculate the number of events expected in the presence of $ZZ\gamma$ couplings, we convoluted generator–level event samples [21] with our fiducial cuts, selection efficiencies, trigger efficiencies, and integrated luminosities in order to derive the expected number of observed events as a function of anomalous couplings parameters. The interference between the Standard Model amplitudes and anomalous coupling amplitudes was taken into account. To obtain more stringent limits, we further required $E_\gamma > \frac{1}{2}\ E_{\mathrm{beam}}$.

Figure 3 shows the 95% C.L. upper limit contours on the pair of CP–conserving form factors for $\Lambda_{\mathrm{Z}} = 500$ GeV assuming the CP–violating form factors to be zero; the corresponding limits on the pair of respective CP–violating form factors are practically the same. Our limits are not very sensitive to the choice of Λ_{Z} for $\Lambda_{\mathrm{Z}} \gg m_{\mathrm{Z}}$. It should be noted that though there is strong interference between the two CP–conserving anomalous couplings and between the two CP–violating couplings, the interference between CP–violating and CP–conserving couplings is negligible. We also show the limits obtained by D0 [22] and the region of parameter space allowed by unitarity. The difference in orientation between our limit and the Tevatron contours [22, 23] results from the fact that the dimension–8 couplings (h_2^{Z}, h_4^{Z}) have a stronger energy dependence than the dimension–6 couplings (h_1^{Z}, h_3^{Z}) and the Tevatron effective center–of–mass energy is higher than that of LEP.

ν_τ Magnetic Moment

Whether or not the τ neutrino has a magnetic moment μ_ν is relevant to determining its basic nature and its magnitude can be used to appraise the possibility that a massive τ neutrino is an important component of dark matter [12].

At the Z resonance, the dominant mechanism for the production of single–photon events via the magnetic moment interaction of the τ neutrino is radiation of a photon from the final–state neutrino or anti–neutrino. The dashed histogram in Figure 2 shows how the expected photon energy spectrum would be modified by a tau neutrino magnetic moment of $5 \times 10^{-6}\ \mu_B$. Since the photon is on–shell, the production rate depends on the magnetic moment form factor at q^2=0. The magnetic moment of only the ν_τ is considered here because existing limits on the magnetic moments of $\nu_{\rm e}$ and ν_μ preclude the possibility of observing them at LEP.

The procedure followed to set limits on the magnetic moment is similar to that followed for ZZγ couplings. Assuming lepton universality in Z decay to neutrinos, the limit on the magnetic moment of the τ neutrino is

$$\mu_\nu < 3.3 \times 10^{-6} \mu_{\rm B} \quad 90\%\ \text{C.L.}$$

This bound applies to both direct and transition magnetic moments.

Other upper limits on the tau neutrino magnetic moment are $4{\times}10^{-6}\mu_{\rm B}$ (90% C.L.) at $q^2 \sim (30\text{GeV})^2$ from PEP and PETRA experiments [24]; $2.7{\times}10^{-6}\mu_{\rm B}$ (95% C.L.) at $q^2 = m_{\rm Z}^2$ from measurements of the Z invisible width at LEP [25]; and $5.4 \times 10^{-7}\mu_{\rm B}$ (90% C.L.) at $q^2 = 0$ from a beam–dump experiment obtained with assumptions on the $\rm D_s$ production cross section and its branching ratio into $\tau\nu_\tau$ [26] .

Upper Limits on the Branching Ratio for Z $\rightarrow \gamma$X

Limits on processes giving rise to single–photon events may be characterized in terms of limits on Z branching ratios in the case that the process is mediated by an on–shell Z. Examples of such processes are the two already described, Z decay into the neutralinos $\tilde{\chi}^\circ_1$ and $\tilde{\chi}^\circ_2$ followed by the decay of $\tilde{\chi}^\circ_2$ into $\tilde{\chi}^\circ_1$ and a photon, and Z decay to an axion and a photon.

We have obtained upper limits on Z decay into energetic single–photon states assuming that the angular distribution of the photons is isotropic. In order to make it possible to read from a single plot limits on both the cases (i) the photons are broadly distributed in energy and (ii) the photon energy distribution emphasizes the upper end of the kinematically allowed range, we have calculated the upper limit as a function of the minimum photon energy $E_{\rm min}$.

Figure 4 shows the upper limit at the 95% C.L. on Z $\rightarrow \gamma$X where the energy of the photon is greater than $E_{\rm min}$. The branching ratio limit ranges to a few parts per million for lower values of $E_{\rm min}$ to one part in a million above $\sim$30 GeV. The limits are not a smooth function of $E_{\rm min}$ because of small event statistics and that the limit has been calculated in steps of 2 GeV for $E_{\rm min}$.

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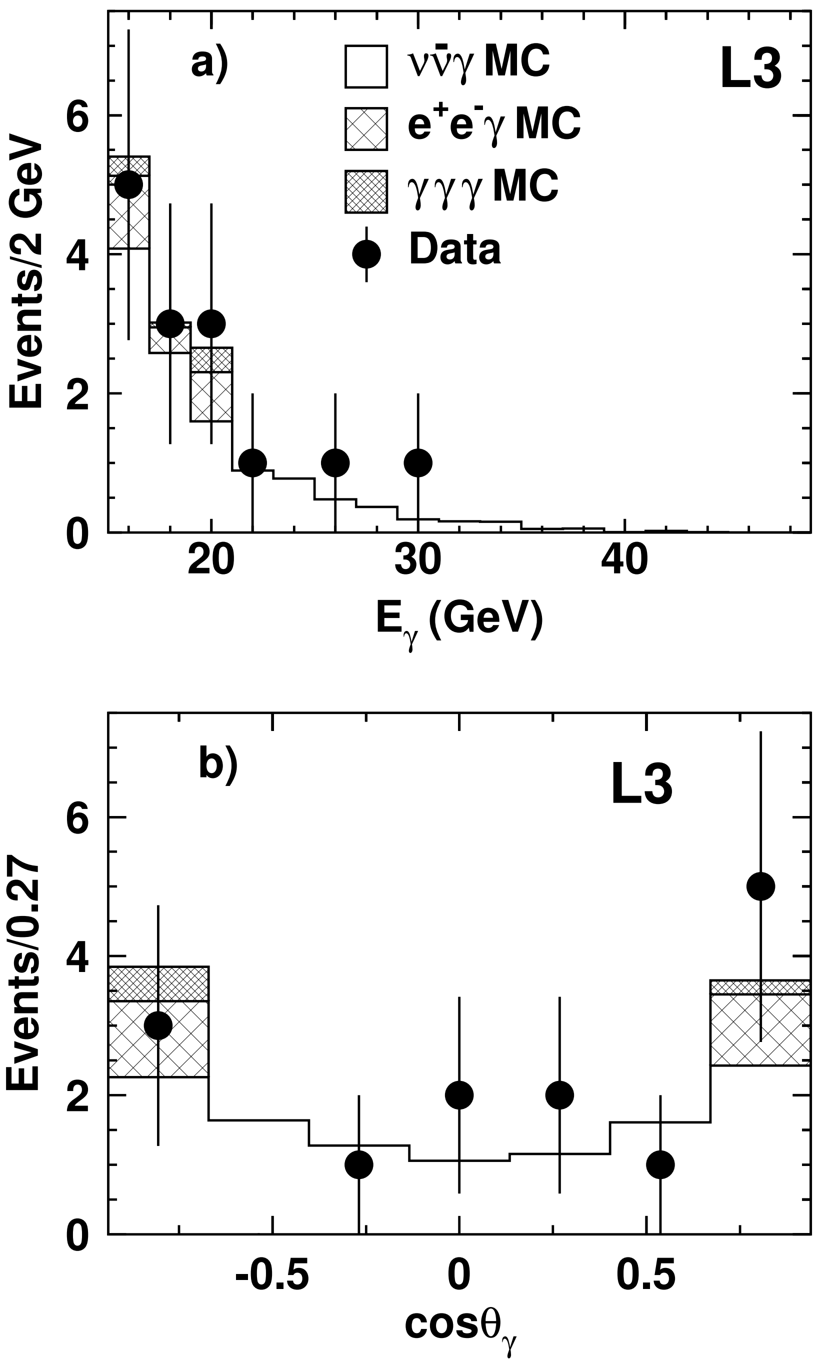

Figure 1: a) Distribution in energy of single–photon candidate events together with expectations based on Monte Carlo simulation of Standard Model processes. b) The $\cos\theta_\gamma$ spectrum of the single–photon candidates and Standard Model expectations.

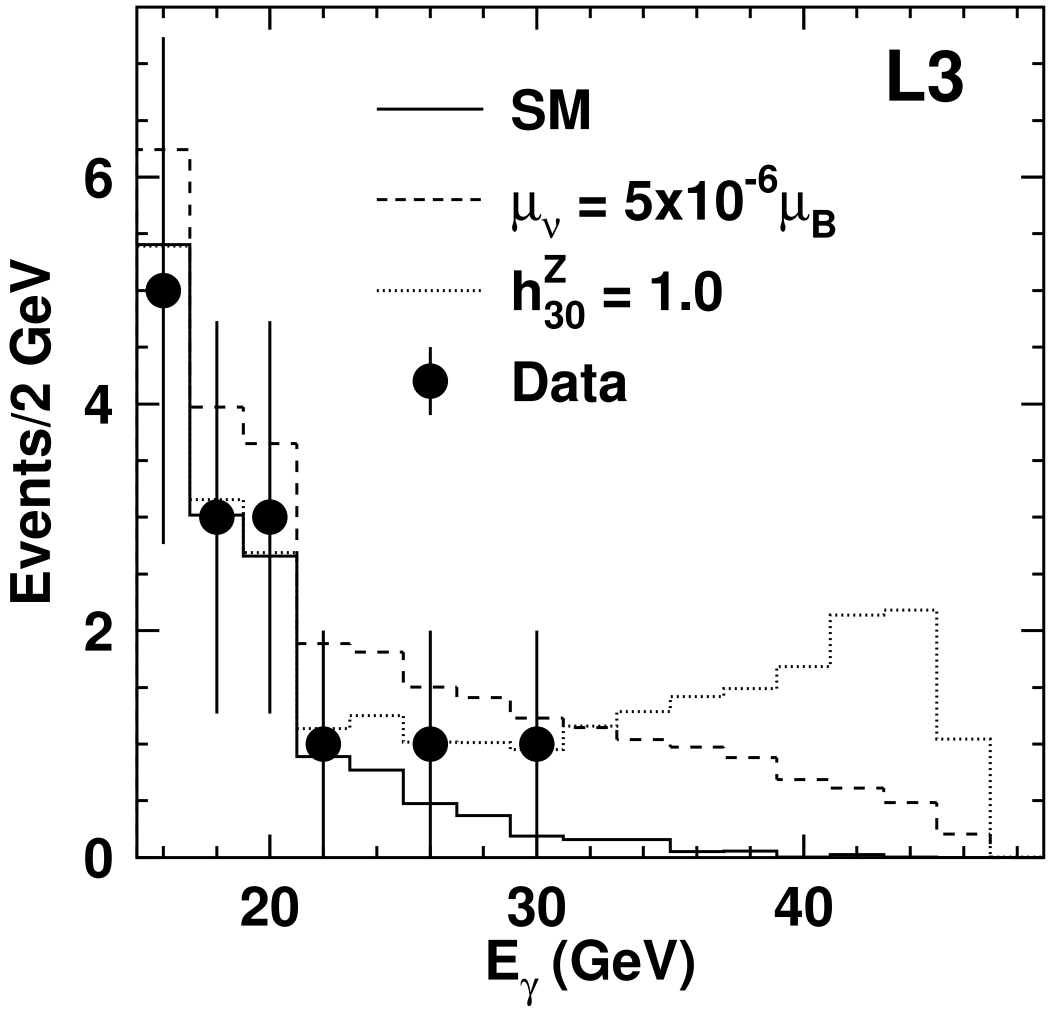

Figure 2: The energy spectra of single–photon events expected in our search from (a) the Standard Model only (solid histogram), (b) the Standard Model modified to give the τ neutrino a magnetic moment of the magnitude indicated (dashed histogram), and (c) the Standard Model extended to include an anomalous $ZZ\gamma$ coupling (dotted histogram). See text for additional description of models. The points show the energy spectrum of the single–photon candidates found in the search.

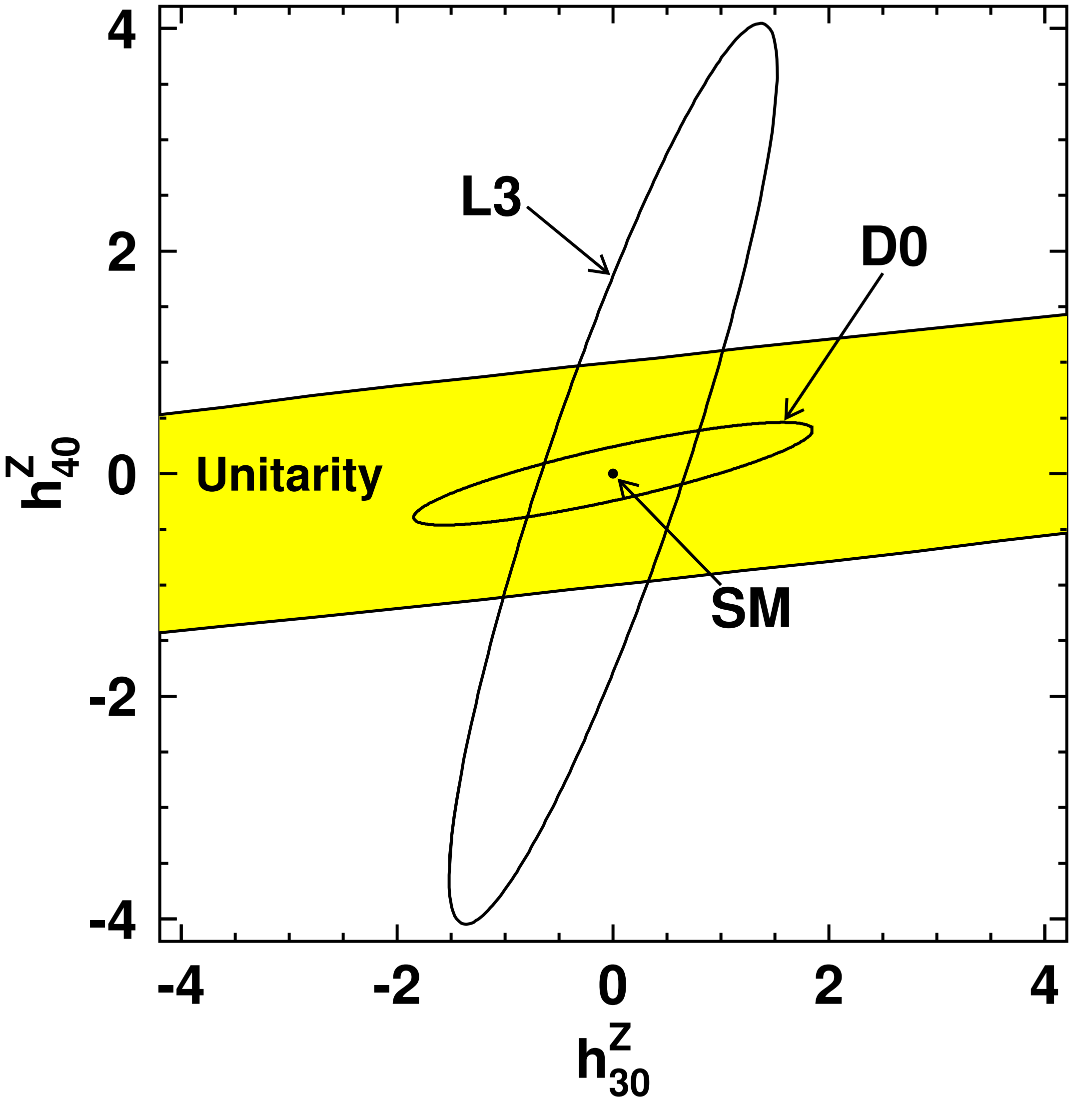

Figure 3: Upper limits at the 95% C.L. on the ZZγ coupling parameters h_{30}^{Z} and h_{40}^{Z} obtained by L3 and by D0 [22] for $\Lambda_{\mathrm{Z}} = 500$ GeV. The Standard Model prediction is indicated by the dot. The region of parameter space allowed by unitarity is shaded.

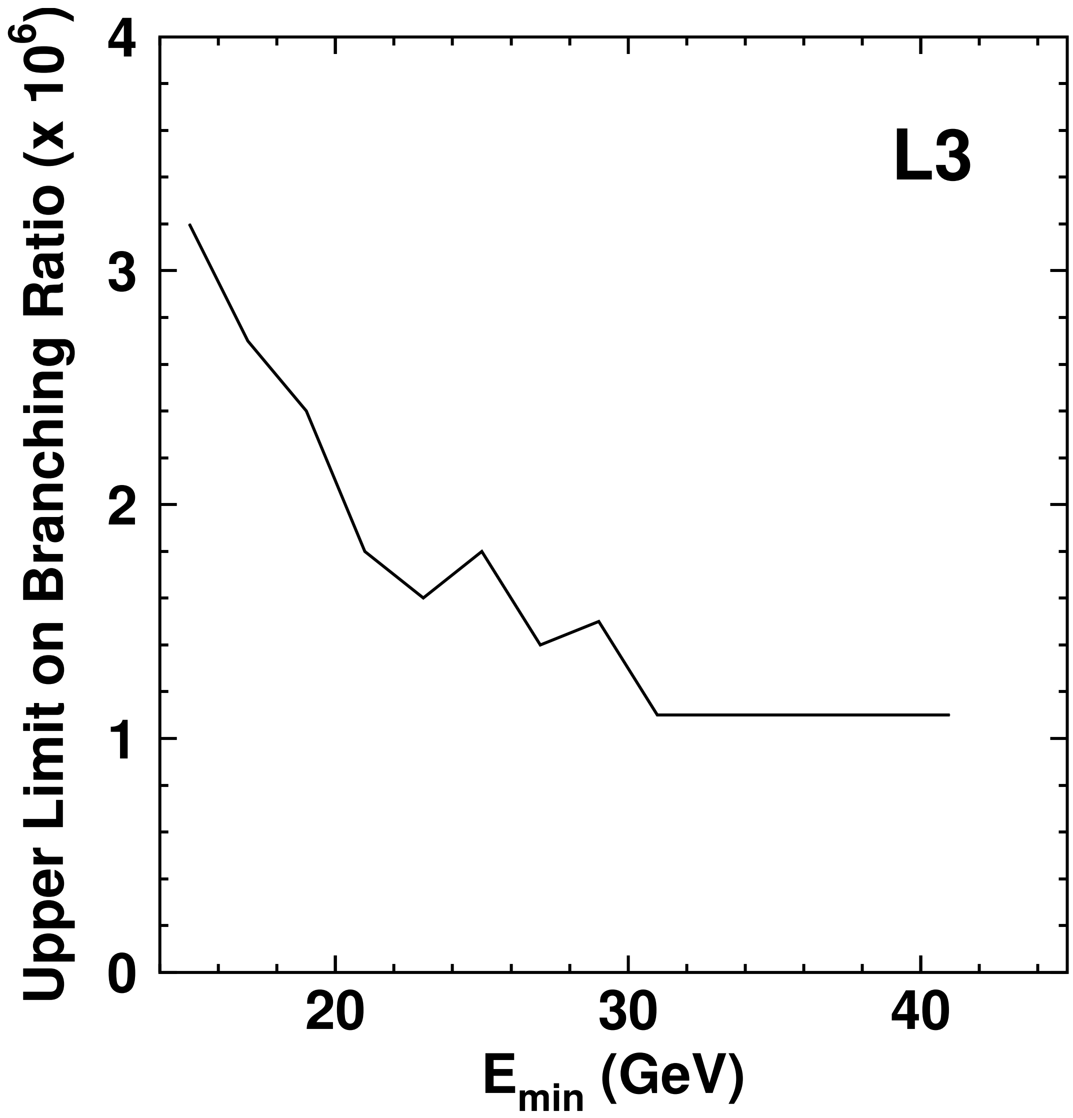

Figure 4: Upper limit at the 95% C.L. on the branching ratio for Z decay to invisible particles and a photon with energy greater than $E_{\rm min}$. The limit has been calculated in steps of 2 GeV for E_{min}.