EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Search For New Particles In Hadronic Events With Isolated Photons

L3 Collaboration

Abstract

A search for the neutral Higgs boson in the processes $e^+e^- \to Z \to H^0\gamma \to q\bar{q}\gamma$ and $e^+e^- \to Z \to Z^*H^0 \to q\bar{q}\gamma\gamma$ has been performed using 2.8 million hadronic Z decays collected with the L3 detector at LEP from 1991 through 1994. No evidence for these processes has been observed. Upper limits at 95% confidence level for the corresponding cross sections have been set and the results have been compared with theoretical predictions beyond the Standard Model.

Introduction

The minimal version of the Standard Model (SM) [1] predicts the existence of a neutral Higgs boson H^0 [2] with an unknown mass. At LEP, a H^0 lighter than the Z could be observable through the processes

$$e^+e^- \to Z \to H^0\gamma, \qquad H^0 \to q\bar{q}, \tag{1}$$

and

$$e^+e^- \to Z \to H^0Z^*, \qquad H^0 \to \gamma\gamma, \qquad Z^* \to q\bar{q}. \tag{2}$$

In the SM, reaction (1) occurs at the one-loop level with charged particles inside the loop, the dominant contribution coming from the $W^\pm$ bosons (Figure 1a). The fermion contributions are negligible due to the lower masses involved. Process (2) is also suppressed in the SM framework, since the H^0 decay into two photons proceeds via a similar loop-diagram (Figure 1b). Within the SM the cross section for process (1) is below 0.1 pb and for process (2) below 10^{-2} pb.

However, in several extensions of the Standard Model, these branching ratios can be significantly enhanced. For example in the Minimal Supersymmetric Standard Model (MSSM) the loop-diagrams of processes (1) and (2) may contain supersymmetric particles (e.g. charginos), resulting in branching ratios which can be increased by up to a factor of 3 [3,4].

A non-standard symmetry breaking may also lead to anomalous interactions of the Higgs with the electroweak gauge bosons affecting the Higgs production and decay mechanisms. The anomalous interactions can be described by an effective dimension-six Lagrangian $\mathcal{L}_{\text{eff}} = \sum_1^7 \frac{f_i}{\Lambda^2}\mathcal{O}_i$, where $\mathcal{O}_i$ are the operators representing the anomalous couplings, Λ is the typical energy scale of the interactions and f_i are constants defining the strength of each term [5]. Whereas in the SM the decay $H^0 \to \gamma\gamma$ occurs at the one-loop level, dimension-six operators contribute at the tree level and can therefore lead to large deviations from the SM. Low energy experiments provide a measurement of some of the coefficients f_i/Λ^2, typical values being of $O(1\ \text{TeV}^{-2})$ with some of them being as large as $O(100\ \text{TeV}^{-2})$. The decay width $\Gamma(H^0 \to \gamma\gamma) \propto (f_i/\Lambda^2)^2$, and for some combinations of the coefficients the branching ratio $\Gamma(H^0 \to \gamma\gamma)$ can be enhanced by a factor as large as 10^4 [5]. Similarly, the decay $Z \to H^0\gamma$ (one-loop level in the SM) is sensitive to such anomalous couplings and can therefore be largely enhanced by the dimension-six contributions occurring at the tree level.

In addition, in some composite models like the Strongly-Coupled Standard Model (SCSM) the branching ratios for reactions (1) and (2) can differ from the SM values [6,7]. Assuming a scale factor Λ characterising the SCSM interaction to be about 300 GeV, the branching ratio $\Gamma(Z \to H^0\gamma)$ is enhanced by a factor of 100 at $M_{H^0} = 60$ GeV leading to measurable cross sections at LEP [6].

This search extends to any scalar boson decaying like the Higgs boson in (1) and (2).

The large number of Z decays collected with the L3 detector at LEP allows a search for these rare processes to be conducted. This search has been carried out by studying hadronic events with one or two isolated hard photons in the final state. Previous results for these searches from the L3 and the other LEP collaborations are reported in references [8,9]. The results reported in this paper update our previous measurements and are obtained using events collected at center-of-mass energies in the range $91.0 \leq \sqrt{s} \leq 91.5$ GeV from 1991 through 1994 and corresponding to a total integrated luminosity of 96.8 pb^{-1}.

The L3 Detector

The L3 detector consists of a silicon microvertex detector, a central tracking chamber, a high resolution electromagnetic calorimeter composed of BGO crystals, a barrel of scintillation counters, a uranium hadron calorimeter with proportional wire chamber readout, and an accurate muon chamber system. These detectors are installed in a 12 m diameter magnet which provides a solenoidal field of 0.5 T and a toroidal field of 1.2 T. Luminosity is measured with a forward-backward BGO calorimeter on each side of the detector. A detailed description of each detector subsystem and its performance is given in [10,11].

The electromagnetic calorimeter consists of 10734 BGO crystals divided into a barrel with a polar angle coverage $42^\circ \leq \theta \leq 138^\circ$ and two endcaps corresponding to the polar angle coverage $10^\circ \leq \theta \leq 37^\circ$ and $143^\circ \leq \theta \leq 170^\circ$ For electrons and photons of more than 5 GeV the energy resolution is less than 2% with an angular resolution better than 2 mrad.

The response of the L3 detector is modelled with the GEANT 3.15 detector simulation program [12] which includes the effects of energy loss, multiple scattering and showering in the detector materials and in the beam pipe as well as the time-dependent inefficiencies of the various subdetectors.

Selection of Hadronic Events with Hard Photons

The selection of $e^+e^- \rightarrow$ hadrons events is based on the energy measured in the electromagnetic and hadronic calorimeters.

We measure the total visible energy (E_{vis}) and the energy imbalances parallel ($E_{||}$) and perpendicular ($E_\perp$) to the beam direction. We select an event to be hadronic if it satisfies the following cuts:

- $N_{clusters} > 12$,
- $0.6 < E_{vis}/\sqrt{s} < 1.4$,
- $E_\perp/E_{vis} < 0.4$,
- $|E_{||}|/E_{vis} < 0.4$.

Only clusters with energy greater than 100 MeV have been used. Since the number of clusters is proportional to the number of particles in the event, the cut on N_{clusters} serves to reject low multiplicity events, which are mainly leptonic or two-photon events.

Applying these cuts to 2.2 million fully simulated events, we find that 98% of the hadronic Z decays are accepted. The Monte Carlo hadronic events were generated using JETSET 7.3 [13] with parton shower and string fragmentation. In order to reduce the contribution from initial state radiation we restrict our study to the events produced near the Z peak corresponding to a center-of-mass energy $91.0 \leq \sqrt{s} \leq 91.5$ GeV. We select 2.8 million hadronic events. The photon candidates are selected from the previous event sample by requiring the following criteria on reconstructed clusters in the electromagnetic calorimeter:

- $E_{\text{cluster}} > 5$ GeV,
- $17^\circ \leq \theta_\gamma \leq 35^\circ$, or $45^\circ \leq \theta_\gamma \leq 135^\circ$, or $145^\circ \leq \theta_\gamma \leq 163^\circ$,
- no track associated to the cluster.

The cut on the polar angle θ_γ is chosen such that an electromagnetic shower is well contained either in the endcaps or in the barrel. The matching of tracks to electromagnetic clusters is performed in the plane transverse to the beam, by extrapolating the track to the estimated position of the cluster and then measuring the azimuthal separation at this radius.

Most of the photons produced in hadronic Z decays come from fragmentation products, mainly π^0's and η's decaying into photons. To reduce significantly this contamination we isolate the photon candidates by requiring no other electromagnetic cluster with an energy above 40 MeV in a cone of half-angle 15° around the candidate direction.

To improve the neutral hadron rejection, we also use a neural network classifier [14] to discriminate single photon showers from multi-photon showers produced in the electromagnetic calorimeter. This cut accepts 90% of the photons while rejecting from 55% up to 70% of the neutral hadrons for 20 GeV clusters; the rejection rate is higher in the BGO barrel (65% – 70%) than in the endcaps (55% – 65%) due to the more complex endcap geometry.

From the 2.8 million hadronic events studied, 11538 events with 11567 photon candidates pass these selection criteria. According to Monte Carlo simulations, approximately 77% of the selected photon candidates originate from final state radiation, 11% from initial state radiation and 12% are due to neutral hadrons faking a single photon. These three background sources are irreducible.

Search for a Narrow Resonance

The signature for process (1) is a monochromatic photon accompanied by hadrons. Since the Z produced in e^+e^- collisions at LEP is at rest, the energy (E_γ) of the photon is determined by the mass of the resonance (M_H) using the following formula:

$$M_\mathrm{H}^2 = M_\mathrm{recoil}^2 = m_\mathrm{Z}^2 - 2E_\gamma m_\mathrm{Z}, \tag{3}$$

where M_recoil denotes the mass of the recoiling hadronic system and m_Z is the Z mass. The very good energy resolution of the BGO calorimeter can be used to determine the mass of the resonance. This translates into a mass resolution ranging from 0.2% for a 80 GeV resonance mass up to 13% for a 20 GeV mass.

We use the PYTHIA 5.6 event generator [15] to simulate the process (1) for the Higgs mass values of 30, 40, 60 and 80 GeV. The H^0 was assumed to decay isotropically. The events were passed through the full detector simulation. The selection efficiencies for signal events obtained with the four mass values with an overlaid fit of a second order polynomial are shown in Figure 2. The efficiency varies from 58% to 75%.

The dominant systematic error in determining the efficiency is due to hadronization uncertainties. This is estimated by using a different fragmentation scheme, based on cluster fragmentation implemented in the HERWIG QCD model [16]. We estimate the uncertainty as the difference between the two model predictions for selecting $q\bar{q}\gamma$ events with the previous cuts. This gives an error of about 2% on the efficiency. Other systematic effects can be neglected.

Process (1) would appear as a peak in the M_recoil distribution. The background is estimated from the data so as not to introduce systematic effects from uncertainties in Monte Carlo expectations: an exponential plus a second order polynomial is fit, see Figure 3. Such a fit, performed over a mass range much wider than the expected signal width, would not be affected by the possible presence of a resonance peak.

We have searched for a signal in the recoil mass spectrum by performing several fits each with a gaussian signal centered at a given M_H over a polynomial background. The width of the gaussian depends on $M_{\rm H}$ and is determined using the detector resolution. Non-gaussian tails in the resolution reduce the efficiency by 3% and are accounted for.

The analysis has been performed separately for Higgs mass values ranging from 20 to 60 GeV and from 60 to 80 GeV. This is due to the fact that for low Higgs mass values (high photon energies) the mass resolution, is larger than for higher Higgs mass values. In addition, the energy distribution of photons decreases almost exponentially, therefore, in order to perform a reliable fit for the background, a larger bin size is needed for higher photon energies (lower Higgs masses). For the $M_{\rm recoil}$ spectrum we therefore use 0.7 GeV bins for $M_{\rm H} < 60$ GeV and 0.3 GeV bins for $M_{\rm H} > 60$ GeV. The $M_{\rm recoil}$ spectrum together with the fit for the background is shown in Figure 3.

No evidence for a Higgs signal is visible through this process. The 95% C.L. upper limit for the cross section $\sigma(\rm e^+e^- \rightarrow H^0\gamma) \times Br(H^0 \rightarrow q\bar{q})$ is presented in Figure 4 as a function of the $\rm H^0$ mass together with predictions from different models. In calculating the upper limit we have conservatively lowered the efficiency by one standard deviation. The limit is one to two orders of magnitude higher than the Standard Model expectation while it is two to three times the maximum possible MSSM value for a Higgs mass below 50 GeV. As a result of this search it is possible to exclude combinations of the coefficients f_i in the model involving the dimension-six Lagrangian which give cross sections larger than our obtained upper limit. This search also excludes the Strongly Coupled Standard Model (SCSM) if the scale factor Λ is less than 100 GeV.

Search for a Scalar Boson Decaying Into Two Photons

The expected signature for process (2) is two isolated energetic photons accompanied by hadrons. The event sample is obtained from the previous one by requiring at least two photon candidates with an energy greater than 10 GeV. No events with three photon candidates pass these cuts. The photon energy distribution of the Monte Carlo $\rm H^0$ signal, together with the distribution obtained from data before the cut is applied, is shown in Figure 5. The corresponding clusters should be separated by at least 40° in space angle and should be separated from the nearest hadronic jet by more than than 30°. The jets are reconstructed using the JADE [17] algorithm with $\rm y_{\it cut}$=0.05 excluding the isolated photon candidates from the reconstruction. The last two cuts have been optimised using Monte Carlo events for hadronic Z decays and for the reaction under study.

From the complete data sample we select 7 events. The main characteristics of these events are summarised in Table 1.

Process (2) for the five Higgs mass values 20, 30, 40, 50 and 60 GeV has been simulated as before. The events have been passed through the full L3 detector simulation to determine the selection efficiencies which are shown in Figure 6 with an overlaid fit of a second order polynomial. The selection efficiencies vary between 16% at 20 GeV and 34% at 50 GeV. We use the same systematic uncertainty on the fragmentation process as in the $\rm Z \rightarrow H^0\gamma$ case.

The $\gamma\gamma$ invariant mass resolution is 3% for $M_{\rm H} = 10$ GeV and 2% for $M_{\rm H} > 30$ GeV.

The same selection applied to the 2.16 million hadronic Z decays generated with Monte Carlo retains only two events. It should be noticed that the JETSET prediction for the rate of final state photons and isolated neutral hadrons in hadronic events is lower than experimentally observed, the discrepancy being 15%–29% [14]. Due to this discrepancy, the Monte Carlo background for $\rm q\bar{q}\gamma\gamma$ events is underestimated. We have therefore estimated the background for the $\gamma\gamma$ invariant mass distribution by using the experimentally determined photon energy

$E_{\gamma,1}$ (GeV)	$E_{\gamma,2}$ (GeV)	$\Delta\Phi'$ (deg)	$M_{\gamma\gamma}$ (GeV)
29.1	15.3	97.5	31.7
35.4	26.4	132.8	56.0
10.4	16.5	135.6	24.3
31.9	38.7	147.4	67.5
22.4	14.4	119.3	31.0
29.6	11.0	84.4	24.3
13.3	36.9	125.7	39.4

Table 1: Events with two isolated photon candidates. $E_{\gamma,1}$ and $E_{\gamma,2}$ denote the energies of the photons, $\Delta\Phi'$ is the space angle between the photon directions and $M_{\gamma\gamma}$ is the invariant mass of the photon pair.

distribution in $\mathrm{q\bar{q}}\gamma$ events. We assume that the two energetic photons in a hadronic event are produced independently of each other. The $\gamma\gamma$ invariant mass distribution for the background obtained following this method is in good agreement with the observed $\gamma\gamma$ invariant mass distribution, the agreement being independent of the event selection criteria. The estimated number of background events corresponding to the number of hadronic events in the data is 4.8. However, in calculating the upper limit for the corresponding cross section, this background can be neglected since the corresponding events are distributed over several $\gamma\gamma$ invariant mass bins. The background contribution to the cross section upper limit is estimated to be of the order of 3% and is neglected.

No clear signal for $\mathrm{H^0} \rightarrow \gamma\gamma$ is seen. The 95% C.L. upper limit for the cross section $\sigma(\mathrm{e^+e^-} \rightarrow \mathrm{H^0} + \mathrm{hadrons}) \times \mathrm{Br}(\mathrm{H^0} \rightarrow \gamma\gamma)$ and its comparison to different theoretical predictions is presented in Figure 7 as a function of the $\mathrm{H^0}$ mass. In calculating the upper limit we have conservatively lowered the efficiency by one standard deviation.

The limit is more than two orders of magnitude higher than the Standard Model expectation. As for the other search it is possible to exclude the combinations of coefficients f_i in the model involving a dimension-six Lagrangian which give cross sections higher than our upper limit. The Strongly Coupled Standard Model is excluded for the scale factor Λ less than 100 GeV.

Conclusion

No evidence of a Higgs boson produced in the reactions $\mathrm{e^+e^-} \rightarrow \mathrm{Z} \rightarrow \mathrm{H^0}\gamma$, $\mathrm{H^0} \rightarrow \mathrm{q\bar{q}}$ and $\mathrm{e^+e^-} \rightarrow \mathrm{Z} \rightarrow \mathrm{H^0Z^*}$, $\mathrm{H^0} \rightarrow \gamma\gamma$, $\mathrm{Z^*} \rightarrow \mathrm{q\bar{q}}$ is observed in the data collected at LEP with the L3 detector during the period from 1991 through 1994 with an integrated luminosity of 96.8 $\mathrm{pb^{-1}}$.

We set upper limits on cross sections for these two processes. Our 95% C.L. limit for $\sigma(\mathrm{e^+e^-} \rightarrow \mathrm{H^0}\gamma) \times \mathrm{Br}(\mathrm{H^0} \rightarrow \mathrm{q\bar{q}})$ is in the range 0.3 to 1.0 pb for Higgs mass values between 20 and 80 GeV.

The 95% C.L. upper limit on the cross section $\sigma(\mathrm{e^+e^-} \rightarrow \mathrm{H^0} + \mathrm{hadrons}) \times \mathrm{Br}(\mathrm{H^0} \rightarrow \gamma\gamma)$ is in the range 0.1 to 0.3 pb for Higgs mass values between 20 and 70 GeV.

Models predicting large enhancement of these processes with respect to the Standard Model are excluded in the mass range 20 GeV $\leq M_\mathrm{H} \leq$ 80 GeV. The two measured limits exclude combinations of the coefficients f_i in the model involving a dimension-six Lagrangian which give cross sections higher than our measured limits. Our search also excludes the Strongly

Coupled Standard Model if the scale factor Λ is less than 100 GeV.

This study improves our previous limits [8] by one order of magnitude. The results obtained can be extended to any neutral scalar boson decaying into the same final states as the Higgs boson.

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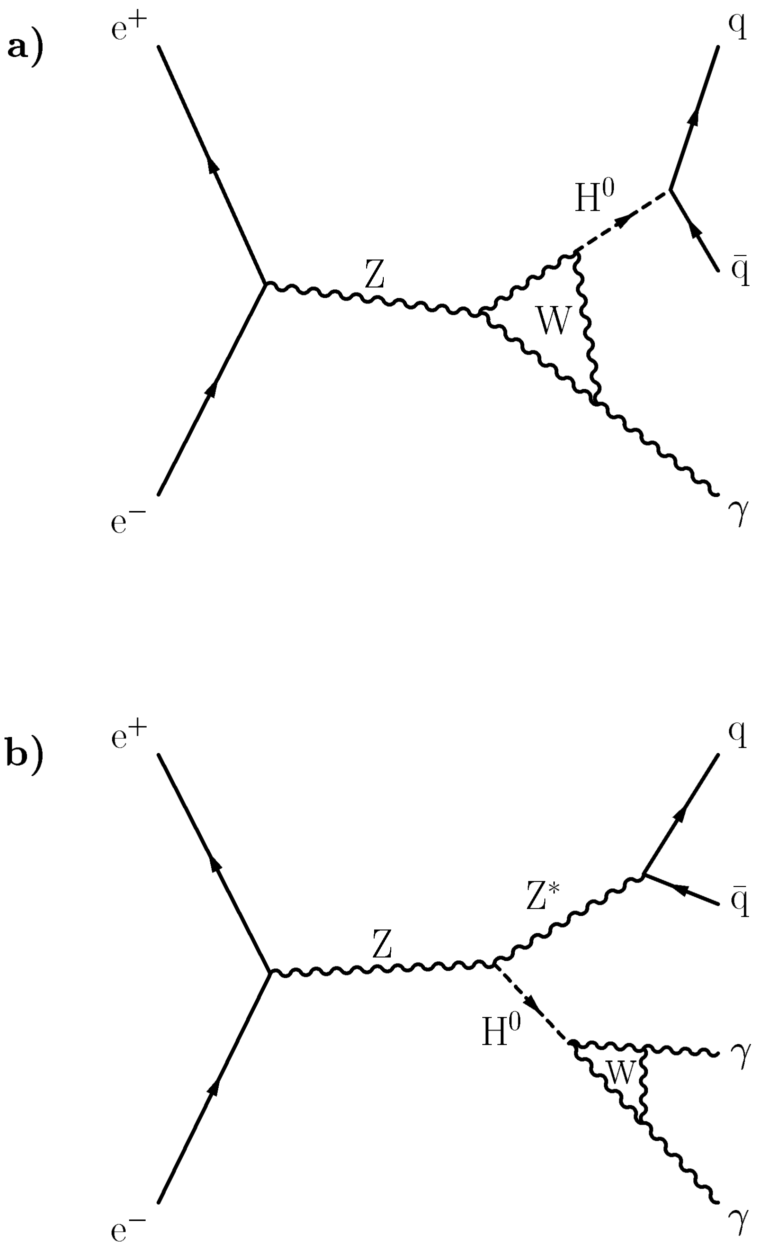

Figure 1: Feynman diagrams for the process (a) $e^+e^- \rightarrow Z \rightarrow H^0\gamma$ with $H^0 \rightarrow q\bar{q}$ and (b) $e^+e^- \rightarrow Z \rightarrow H^0Z^*$ with $H^0 \rightarrow \gamma\gamma$, $Z^* \rightarrow q\bar{q}$. In the Standard Model the Z decay in (a) and the H^0 decay in (b) occur via charged boson or fermion (not shown on the plot) loops.

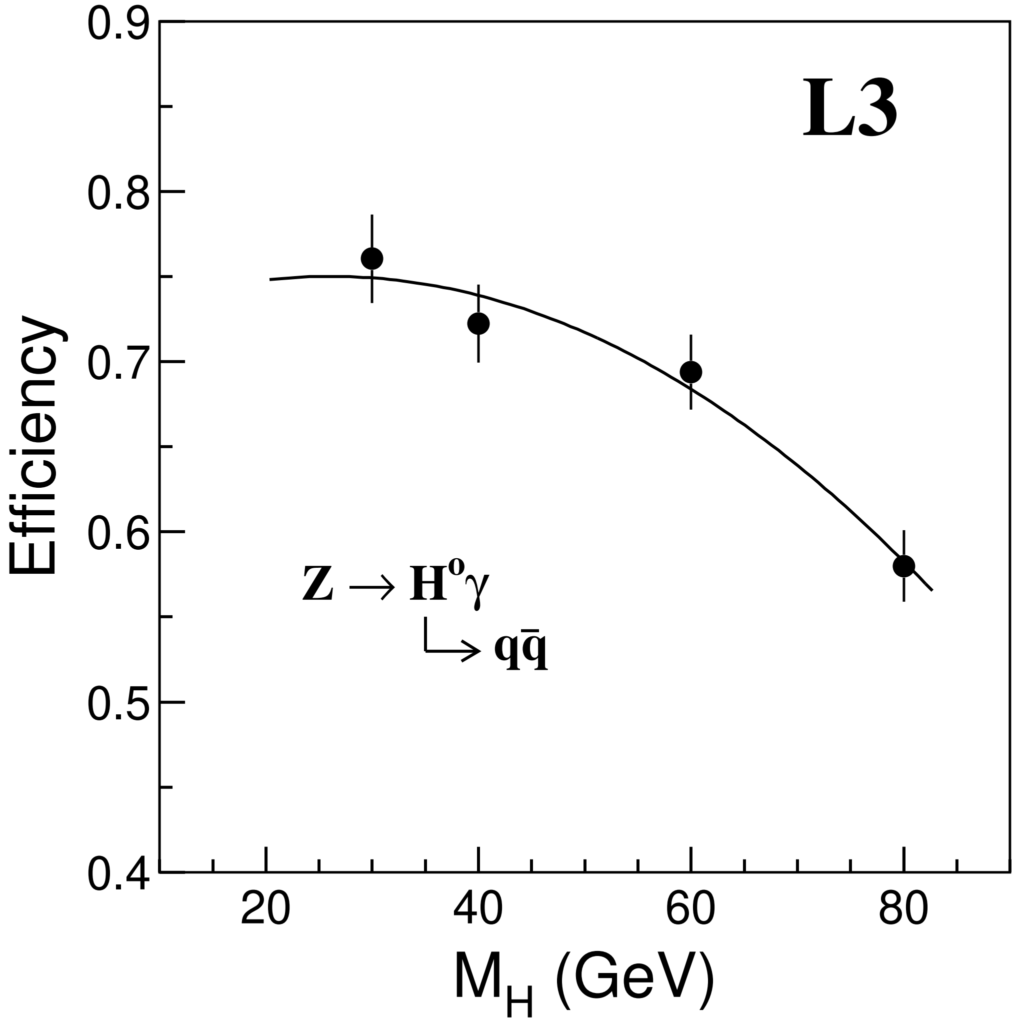

Figure 2: Selection efficiency for the process Z $\rightarrow$ H$^0\gamma$, H^0 $\rightarrow$ q$\bar{\mathrm{q}}$ as a function of the Higgs mass. The errors shown include statistical and systematic uncertainties.

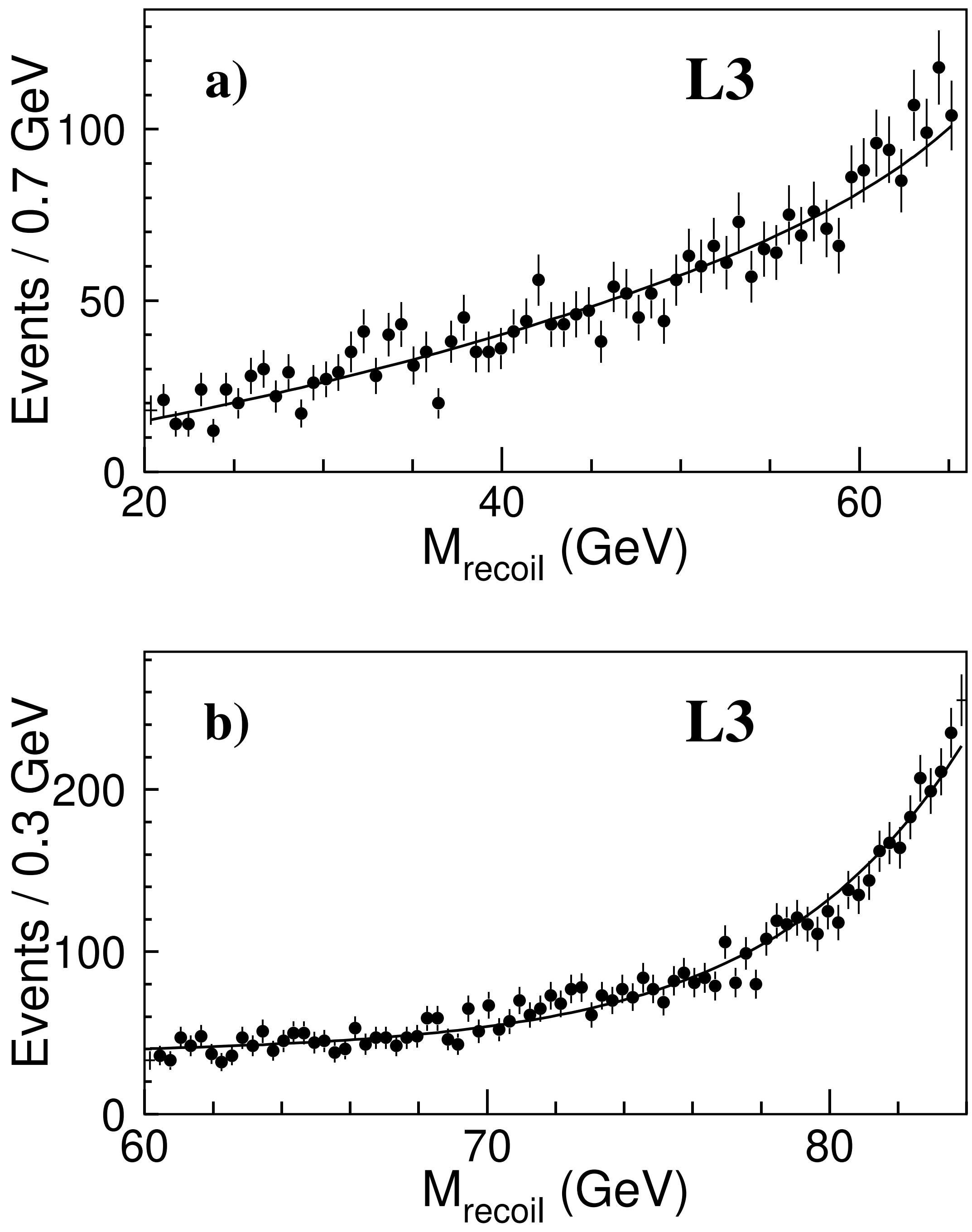

Figure 3: The recoiling hadronic mass spectrum obtained from the photon energy together with a fit for the background for two ranges of mass values (a) $M_{\mathrm{recoil}} < 65$ GeV and (b) $M_{\mathrm{recoil}} > 60$ GeV.

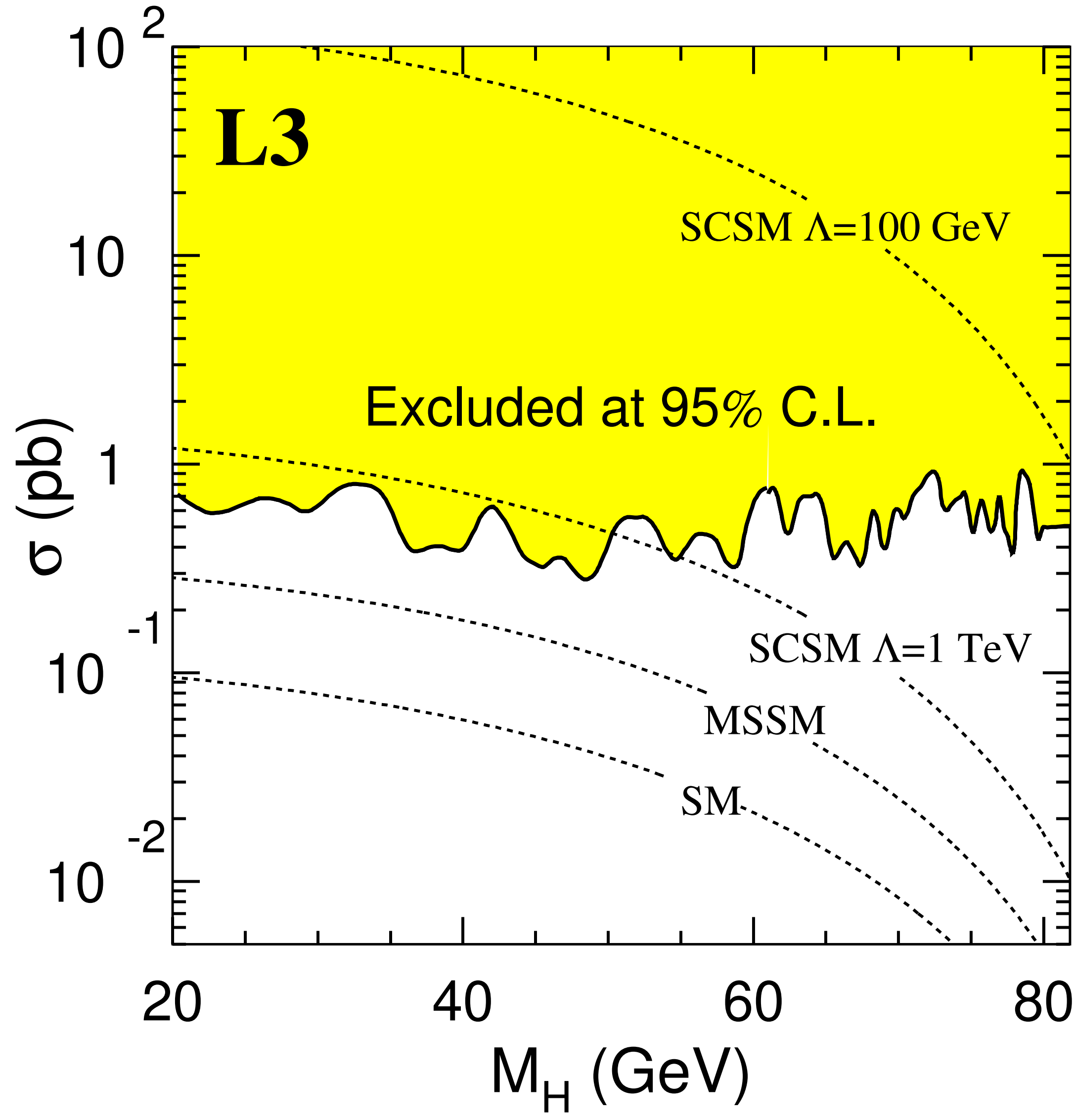

Figure 4: The 95% C.L. upper limit for the cross section $\sigma(e^+e^- \to H^0\gamma)\times Br(H^0 \to q\bar{q})$ together with some theoretical predictions. SM – Standard Model, MSSM – Minimal Supersymmetric Standard Model, SCSM – Strongly Coupled Standard Model. For the MSSM prediction we present the maximal allowed enchancement of the cross section as given in [3]. For the SCSM, the compositeness scale Λ is noted.

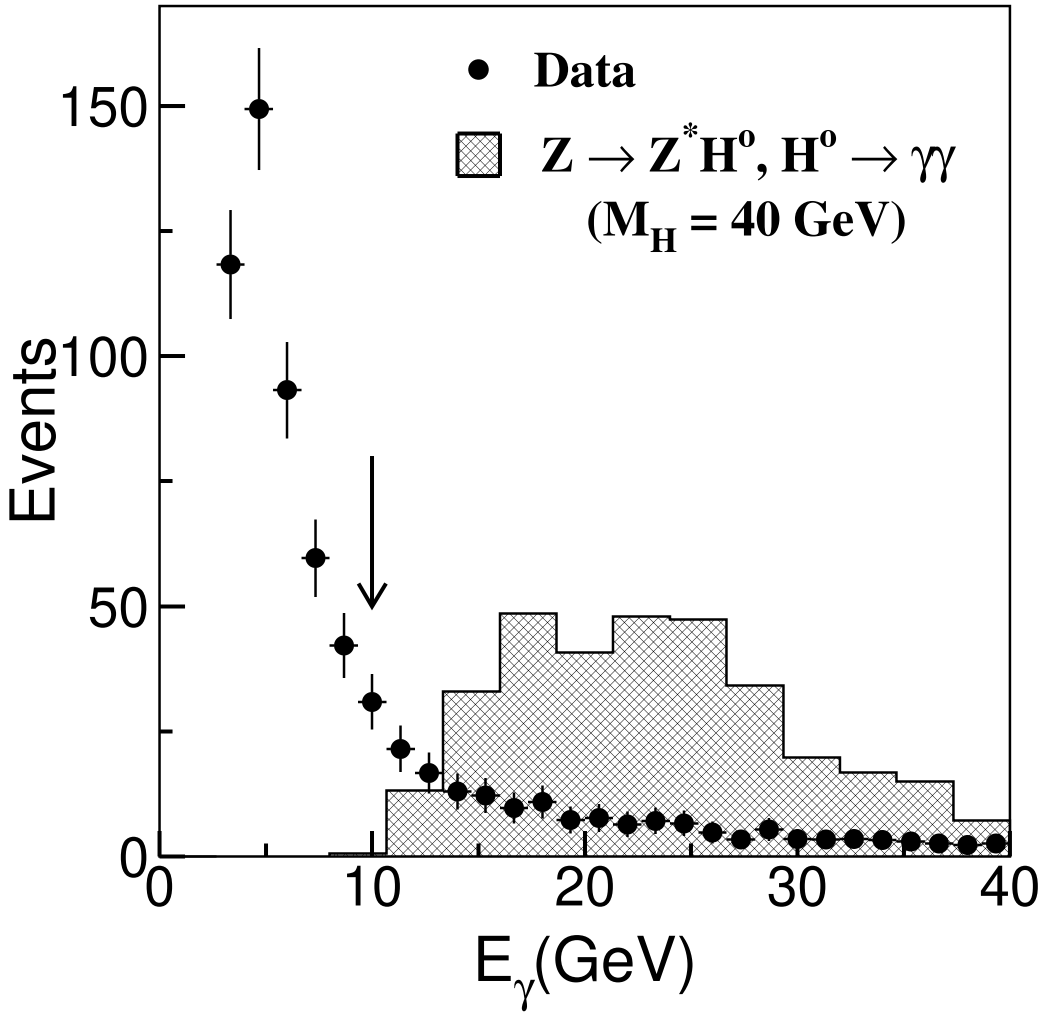

Figure 5: The energy distribution of photon candidates in hadronic events with two or more photons for $M_{H^0} = 40$ GeV Monte Carlo signal together with the corresponding distribution obtained from data. The arrow corresponds to the cut used. The relative normalization of the distributions is arbitrary.

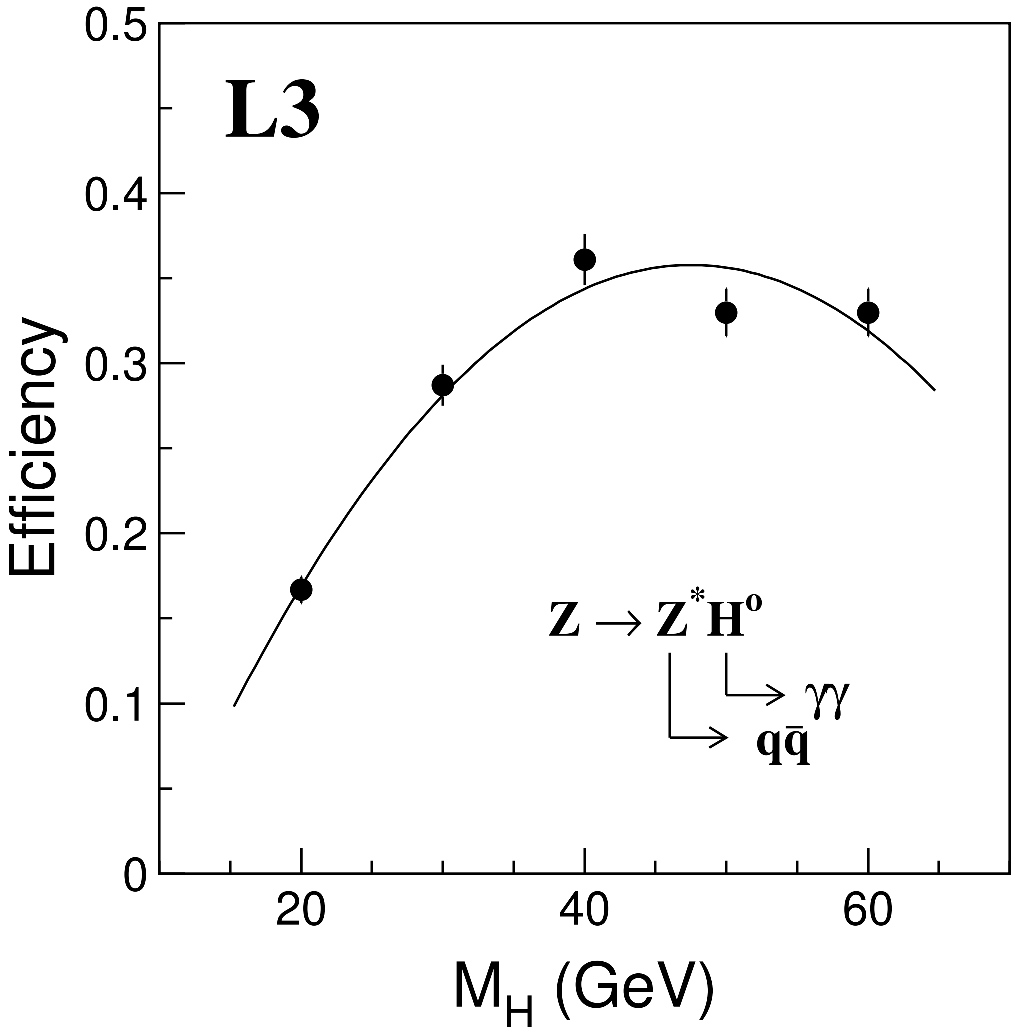

Figure 6: Selection efficiency for the process $Z \rightarrow H^0 q\bar{q}$, $H^0 \rightarrow \gamma\gamma$ as a function of the Higgs mass. The errors shown include statistical and systematic uncertainities.

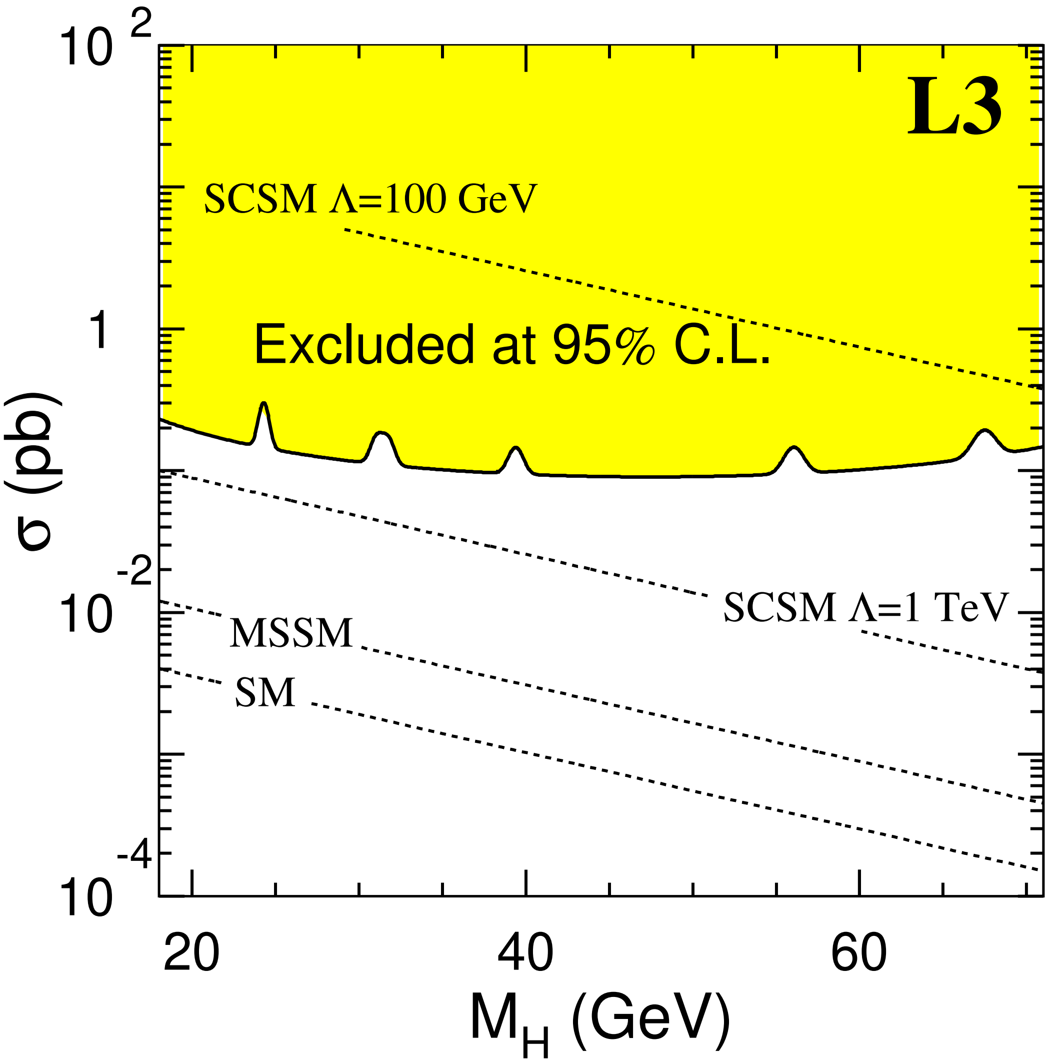

Figure 7: The 95% C.L. upper limit for the cross section $\sigma(e^+e^- \to H^0 + \text{hadrons}) \times Br(H^0 \to \gamma\gamma)$ together with some theoretical predictions. SM – Standard Model, MSSM – Minimal Supersymmetric Standard Model, SCSM – Strongly Coupled Standard Model. For the MSSM prediction we present the maximal allowed enchancement of the cross section as given in [4]. For the SCSM, the compositeness scale Λ is noted.