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Search for the neutral Higgs boson in Z^0 decay

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We have searched for the neutral Higgs boson produced in the decays of the Z^0 through the processes $Z^0 \to H^0\mu^+\mu^-$, $Z^0 \to H^0e^+e^-$ and $Z^0 \to H^0\nu\bar{\nu}$. The data sample analysed corresponds to about 50 200 $Z^0 \to$ hadrons. Combining the results of all three processes we exclude a minimal standard model Higgs boson in the mass range $2 < M_{H^0} < 32$ GeV at the 95% confidence level.

1. Introduction

The standard model [1] has been very successful in describing all data concerning electroweak interactions. In this model Z^0 and $W^\pm$ bosons acquire mass through the Higgs mechanism [2] which, in its minimal formulation, predicts the existence of one neutral boson H^0. Although the theory precisely predicts its coupling to both vector bosons and fermions, it leaves unpredicted the value of its mass. If the Higgs boson is lighter than the Z^0, it can be produced in Z^0 decays through the Bjorken bremsstrahlung process [3]:

$$e^+e^- \to Z^0 \to H^0 + Z^{0*} \to H^0 + f\bar{f}$$

where the off shell Z^{0*} decays into a pair of fermions.

In this letter we describe our search for the minimal standard model Higgs boson in the channels $Z^0 \to H^0\mu^+\mu^-$, $Z^0 \to H^0e^+e^-$ and $Z^0 \to H^0\nu\bar{\nu}$ performed at LEP using data collected by the L3 detector during a scan of the Z^0 resonance in the spring of 1990. In this period approximately 50 200 Z^0 decays into hadrons have been detected and they are used here as normalization.

2. The L3 detector

The L3 detector covers 99% of 4π with calorimetry. The detector consists of a central vertex chamber, a high resolution electromagnetic calorimeter composed of BGO crystals, a ring of scintillation counters, a uranium and brass hadron calorimeter with proportional wire chamber readout, and a very accurate muon chamber system. These detectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 T along the beam axis. The detector and its performance are described in detail elsewhere [4,5].

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3. H^0 production and decay

The $e^+e^- \to Z^0 \to H^0 + Z^{0*}$ cross section is predicted by the standard model and depends on the Higgs mass [6]. The Higgs decay partial widths into fermions are also well established for mass of the H^0 greater than 2 GeV [7]. Since the Higgs coupling to fermions is proportional to the square of the fermion mass, the Higgs decays predominantly into $b\bar{b}$ for masses above 11 GeV and into $\tau^+\tau^-$ and $c\bar{c}$ in the mass range 4–11 GeV. Between 2 and 4 GeV it will predominantly decay into $s\bar{s}$. Below 2 GeV non-perturbative effects make the prediction of the branching ratios of the Higgs boson decaying into hadrons and lepton less firm [7], leading to large uncertainties in the detection efficiency of light Higgs. For this reason, although we have searched for the Higgs boson down to the mass values of a few hundred MeV, we are able to determine the efficiency for finding a Higgs in the mass range $M_{H^0} > 2$ GeV.

In order to determine the acceptance of our detector and the efficiency of our selection a Monte Carlo simulation of the above processes has been performed. This simulation includes both initial and final state photon radiation. The decay of the Higgs boson into hadrons has been simulated using the Lund Model (JETSET 6.3) [8]. The response of the detector has been simulated using the L3 detector simulation program [#1]. The simulation includes the effects of energy loss, multiple scattering, interactions and decays in the detector materials and the beam pipe. Resolution and efficiency of the detector are also taken into account.

4. $Z^0 \to H^0 \nu\bar{\nu}$ event selection

In this process a large fraction of the energy is carried by the neutrinos which escape detection. Depending on the Higgs mass and the Lorenz boost, the decay products can either be close to each other appearing as a single jet [#2], or be well separated in space forming two jets. Thus the signature is one jet or two acollinear jets, and large missing energy and transverse momentum.

$e^+e^- \to Z^0 \to H^0\nu\bar{\nu}$ events are detected by the energy trigger, the charged track trigger and by a cluster trigger which requires an angular matching between a charged track and a calorimetric cluster with an energy greater than 3 GeV. The trigger efficiency has been evaluated using two methods. In the first, a simulated trigger has been applied to the Monte Carlo generated $Z^0 \to H^0\nu\bar{\nu}$ events. The second method uses the trigger information from a data sample selected with more relaxed criteria than those described below. The two methods agree within 5% for $M_{H^0} < 15$ GeV where the estimated trigger efficiency is about 80%, and to better than 1% above this mass where the trigger efficiency is close to 100%.

The main sources of background for the $Z^0 \to H^0\nu\bar{\nu}$ process are $Z^0 \to q\bar{q}(g)$, $Z^0 \to \tau^+\tau^-(\gamma)$, $e^+e^- \to e^+e^-q\bar{q}$, beam–gas and beam–wall interactions. Unlike the Higgs events, the hadronic decays of Z^0 are characterized by either two collinear or more than two jets, good energy balance, small missing energy and high multiplicity of energy clusters. $\tau^+\tau^-$ events have high thrust, low multiplicity of energy clusters and back-to-back jets. Four fermion final states are characterized by large longitudinal energy imbalance, low multiplicity of energy clusters and good transverse energy balance. Beam–gas interactions produce tracks in the central tracking detector which do not originate from the beam intersection region and deposit large amounts of energy in the luminosity monitor.

For the selection of $Z^0 \to H^0\nu\bar{\nu}$ events we use the following criteria:

(1) The total energy E_{tot} of the event should be less than 70 GeV. The effect of this cut on $Z^0 \to$ hadrons events is illustrated in fig. 1a;

(2) The transverse energy imbalance should be greater than 28% of E_{tot}. Fig. 1b shows the comparison of the Monte Carlo distributions for $e^+e^-q\bar{q}$ final state events and the 30 GeV Higgs;

[#1] The L3 detector simulation is based on GEANT Version 3.13 (September, 1989), see ref. [9]. The GHEISHA program [10] is used to simulate hadronic interactions.

[#2] Jets are reconstructed using a two step procedure: first adjacent calorimetric hits are combined into *clusters*, then *jets* are formed merging all *clusters* found inside a cone of 35°. Charged tracks are assigned to the nearest jet.

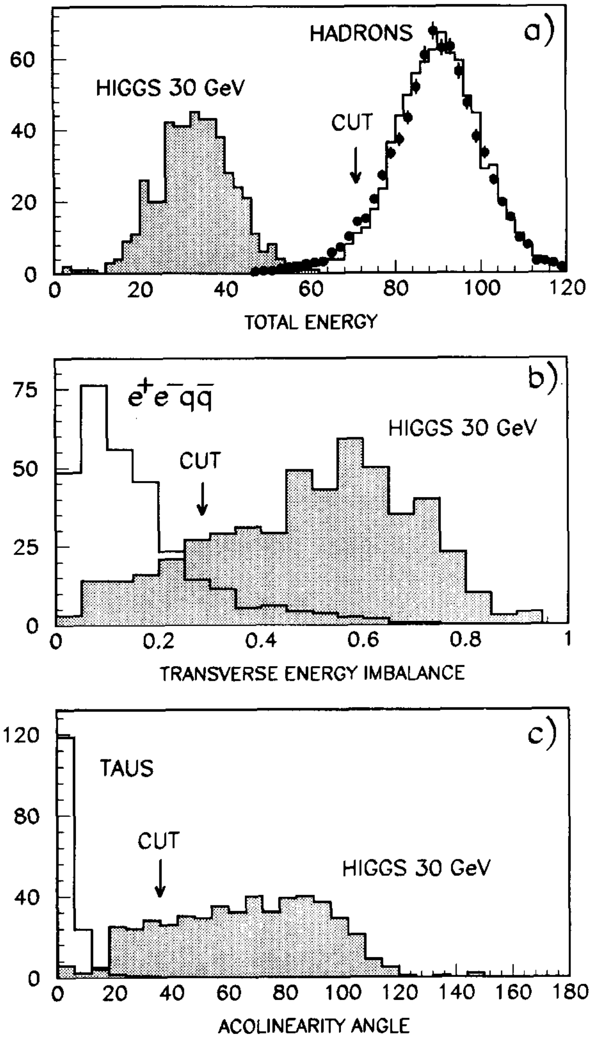

Fig. 1. Comparison between Monte Carlo generated $e^+e^-\to Z^0\to H^0\nu\bar{\nu}$ events for a mass of the Higgs boson of 30 GeV (shaded histogram) and simulated background processes. (a) Total event energy distribution for the processes $e^+e^-\to Z^0\to H^0\nu\bar{\nu}$ and $e^+e^-\to Z^0\to$ hadrons. For the last process data selected according to the criteria described in ref. [5] are also shown as points. (b) Transverse energy imbalance distribution for the process $e^+e^-\to Z^0\to H^0\nu\bar{\nu}$ and $e^+e^-\to e^+e^-q\bar{q}$. (c) Distribution of the acollinearity angle between the two most energetic jets for the processes $e^+e^-\to Z^0\to H^0\nu\bar{\nu}$ and $e^+e^-\to\tau^+\tau^-$. The arrows indicate the position of the cuts used in the event selection. The normalization between the two histograms is arbitrary.

(3) The energy of the third jet (if any) should be less than 5 GeV;

(4) The total number of clusters [5] in the calorimeters should be at least 9 and not more than 45;

(5) For multi-jet events the acollinearity angle between the two most energetic jets should be greater than 35°. In fig. 1c the Monte Carlo distributions of this quantity are compared for τ pairs events and the 30 GeV Higgs;

(6) The thrust of the event should be less than 0.98;

(7) There should be at least one jet with the following properties:

- at least 6 GeV of energy,
- at least 3 calorimetric clusters,
- at least 1 track in the central tracking detector,

inside a 35° cone around the jet axis;

(8) The energy deposited in the luminosity calorimeter should be less than 10% of E_{tot};

(9) The longitudinal energy imbalance should be less than 75% of E_{tot};

(10) There should be at least two charged tracks with transverse momentum greater than 0.5 GeV and the distance of closest approach to the beam axis of less than 5 mm. This cut removes about 4% of the Higgs events for $M_{H^0}=5$ GeV due to inefficiencies of the vertex chamber. For Higgs masses larger than 20 GeV the effect of the vertex chamber inefficiency is negligible.

We observe no events in the data satisfying the above criteria. From the Monte Carlo studies we expect 1.4 background events from $Z^0\to$ hadrons events. This large rejection against hadronic events comes mainly from cut 1, 2 and 5 [5]. We also expect 0.2 events from tau pairs and 0.8 events from four fermion final states.

The dependence of Higgs selection efficiency, including the trigger efficiency discussed above, is plotted versus the Higgs mass in fig. 2.

5. $Z^0\to H^0e^+e^-$ and $Z^0\to H^0\mu^+\mu^-$ event selection

$Z^0\to H^0\ell^+\ell^-$ events are characterized by the presence of two high momentum isolated leptons, coming from the off shell Z^{0*}, recoiling against one or two hadronic jets coming from the H^0 decay.

The two muons are identified requiring two tracks in the muon chambers with $P_\mu > 3$ GeV coming from the vertex and associated with at least one hit in the scintillator barrel in time with the beam crossing. The sum of their momenta should be greater than 20 GeV.

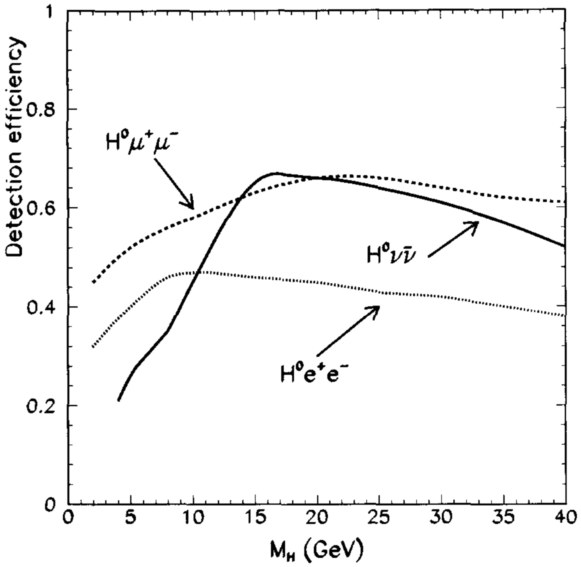

Fig. 2. Detection efficiency for the processes $Z^0 \to H^0\mu^+\mu^-$, $Z^0 \to H^0e^+e^-$ and $Z^0 \to H^0\nu\bar{\nu}$ as a function of the Higgs mass. It includes geometrical acceptance and selection and trigger efficiencies.

The two electrons are identified requiring two electromagnetic clusters in the BGO calorimeter with energy greater than 2 GeV. The sum of their energies should be greater than $40\%\sqrt{s}$ and less than $94\%\sqrt{s}$.

The angle between the two leptons should be between 90° and 177°.

For the detection of the Higgs decay products we require that two calorimetric clusters (of which one is associated with a charged track) are present besides the ones associated with the leptons.

These cuts remove cosmic rays and Z^0 decays in electron, muon and tau pairs. The requirement of at least one charged track not associated to any lepton removes radiative dilepton events. Less than 3% of the Higgs events with $M_{H^0} = 5$ GeV are lost due to inefficiencies of the vertex chamber. This loss becomes negligible for Higgs masses larger than 15 GeV.

The isolation of the two leptons is ensured by requiring that:

- for each electron cluster, at least 95% of the energy measured in the 5×5 array of BGO crystals centred on the most energetic one is contained in the inner 9 crystals;
- for the case of muons no other calorimetric cluster, besides the one associated with the μ, is present in a cone of 35° around at least one muon.

These cuts remove heavy flavour (mainly $b\bar{b}$) events in which both quarks decay into leptons.

In order to increase the acceptance we also search for events in which one of the two muons escapes detection. In this case we require that the following additional conditions be satisfied:

The μ should have a momentum larger than 15 GeV, its angle with respect to the nearest jet should be between 23° and 169° and its $P_\perp$ with respect to the nearest jet should be larger than 10 GeV.

The cuts above remove events containing a muon produced in the decays of hadrons and taus.

The trigger efficiency has been checked using electron, muon and tau pair events and has been found to be close to 100% due to the redundancy of the muon, energy and charged track triggers used.

Two events of the type $e^+e^- \to e^+e^- + X$ pass the above selection criteria. Both events are consistent with the expected rate of four fermion final state processes. One is identified as $e^+e^- \to e^+e^- + \mu^+\mu^-$ which has a measured mass of the dimuon system of 0.6 GeV and is, therefore, outside the mass range under investigation. The second one has a measured missing mass with respect to the e^+e^- pair of 9.5 GeV and it has to be considered as a Higgs candidate.

To determine the expected number of events from Higgs production and from background processes we have performed Monte Carlo calculations which include simulation of the detector. Simulated Higgs events with masses ranging from 2 to 40 GeV have been generated. After applying the same selection criteria as are used for the data, we obtain the selection efficiencies for Higgs events as presented in fig. 2. A study of Monte Carlo events shows that the Higgs candidate is only compatible with Higgs masses below 12 GeV: less than 1% of the events with a Higgs mass larger 12 GeV will give a "measured" missing mass below 9.5 GeV. Therefore we have no candidate for Higgs masses above 12 GeV.

Four fermion events [11] [3] $e^+e^- \to \ell^+\ell^- + q\bar{q}$ are background for Higgs events especially for small Higgs masses. In simulating these events, we have used a value of 5 GeV for the minimum invariant mass of

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[3] The Monte Carlo generator we use, which include all four fermion final state diagrams, has been provided to us by R. Kleiss.

any pair of produced fermions. We expect 0.42 events to pass the previous cuts. Using a smaller value (3 GeV) for the minimum invariant mass we find ~0.8 background events. In order to set a conservative limit, we assume one background event observed and 0.42 expected in the mass range $M_{H^0} < 12$ GeV.

To estimate the background for large Higgs masses we have applied the same selection cuts to simulated $Z^0 \to b\bar{b}$ events, and find 0.7 background events for 50 200 Z^0 hadronic decays. These events are a background for Higgs masses larger than 30 GeV.

6. Results and conclusions

Fig. 3 shows the number of expected events for the processes $Z^0 \to H^0\mu^+\mu^-$, $Z^0 \to H^0e^+e^-$ and $Z^0 \to H^0\nu\bar{\nu}$ as a function of the Higgs mass corresponding to 50 200 $Z^0 \to$ hadrons decays. In order to set a conservative mass limit, we have reduced the number of expected Higgs events by 8% to account for systematic errors coming from uncertainties in the Higgs production cross section, in our event selection and in the trigger and detector efficiency. In fig. 3, the line corresponding to the 95% confidence level limit obtained using Poisson statistics [12] is shown. Combining the results from all three processes, we can exclude a minimal model Higgs boson in the mass range $2 < M_{H^0} < 32$ GeV at the 95% confidence level. This result improves previous published measurements [13].

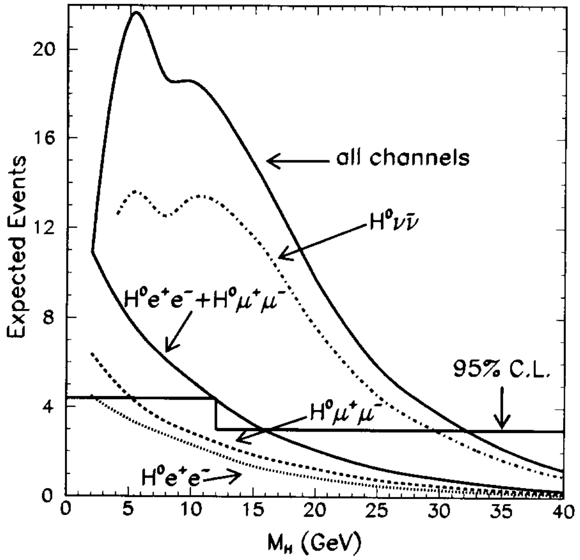

Fig. 3. The number of events expected from the processes $Z^0 \to H^0\mu^+\mu^-$, $Z^0 \to H^0e^+e^-$ and $Z^0 \to H^0\nu\bar{\nu}$ and the sum of the above channels as a function of the mass of the Higgs boson. Also displayed is the 95% confidence level limit.

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