Mass Limits for a Standard Model Higgs Boson in e^+e^- Collisions at LEP

The OPAL Collaboration

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Abstract

A search for the minimal Standard Model Higgs boson has been performed with data from e^+e^- collisions in the OPAL detector at LEP. The analysis is based on 825 nb^{-1} of data taken at center-of-mass energies between 88.3 and 95.0 GeV . The search concentrated on the reactions $e^+e^- \rightarrow (e^+e^- \text{ or } \mu^+\mu^- \text{ or } \nu\bar{\nu})H^0, H^0 \rightarrow (q\bar{q} \text{ or } \tau^+\tau^-)$, for Higgs masses above $3\text{ GeV}/c^2$. No Higgs boson candidates have been observed. The present study excludes the existence of a Standard Model H^0 with mass in the range $3.0 \leq m_H \leq 19.3\text{ GeV}/c^2$ at the 95% confidence level.

1 Introduction

The Standard Model of electro-weak interactions [1] has been corroborated by an impressive number of experimental observations. However, the Higgs boson [2], which is an essential particle in this theory, has to date eluded experimental observation. A minimum of one physical boson must be left after spontaneous symmetry breaking is invoked in order to provide masses for the $W^\pm$ and Z^0 bosons while keeping the theory renormalizable. The minimal model predicts the couplings of the Higgs boson, but not its mass. The Higgs boson mass can nevertheless be bounded from below by using vacuum stability arguments [3]. However, the lower bound vanishes as the top mass approaches $80 \text{ GeV}/c^2$. For top masses exceeding $80 \text{ GeV}/c^2$, the lower bound on m_H changes rapidly with increasing m_t in both first [4] and second [5] order calculations. Searches for the Higgs boson prior to LEP cover the masses up to approximately $5.0 \text{ GeV}/c^2$ [6], though they are model dependent as they rely on estimates of resonant enhancements in the coupling of the Higgs boson to strongly-bound states [7].

A Standard Model Higgs boson is expected to be produced in e^+e^- annihilations in association with a Z^0 , either real or virtual. This process involves the coupling of three point-like particles (ZHZ) which, within the framework of the Standard Model, can be calculated exactly. This calculation predicts the branching ratio for $Z^0 \rightarrow Z^{0*}H^0$ to be in the range of $\sim 10^{-2}$ (for a very light Higgs boson) to $\sim 5 \times 10^{-5}$ (for a Higgs boson of mass $50 \text{ GeV}/c^2$). This relatively high branching fraction, which is due to the proportionality of the Higgs boson coupling to mass, is theoretically robust and therefore permits one to perform a definitive search over a large mass range with only a modest number of Z^0 decays.

Two channels have been used in the analysis presented here. For a Higgs boson search with $m_H \geq 3 \text{ GeV}/c^2$, the decay $e^+e^- \rightarrow \nu\bar{\nu}H^0$, $H^0 \rightarrow f\bar{f}$ ($f = \tau, q$) provides the most sensitive search channel. This is due to its characteristic signature of an asymmetric topology (the di-jet is confined to one hemisphere) resulting from large missing energy and $|\sum \vec{p}_T|$ (henceforth p_T) [8], and because there is an appreciable (20%) branching fraction of the Z^0 into $\nu\bar{\nu}$. The channel $e^+e^- \rightarrow (e^+e^- \text{ or } \mu^+\mu^-)H^0$, $H^0 \rightarrow f\bar{f}$ ($f = \tau, q$) also has a simple experimental signature with high efficiency for detection, although it has a smaller branching ratio. For H^0 masses below $3 \text{ GeV}/c^2$, the hadronization mechanism for H^0 decays is strongly model dependent [7][9], and this prevents reliable simulation of the selection efficiencies. Therefore, other approaches must be used to study this mass region. Such a study is not considered in the present publication.

2 The OPAL detector

The data were recorded at the CERN e^+e^- collider LEP during its Fall 1989 run, and correspond to an integrated luminosity of 825 nb^{-1} . The measurements reported here made use of the OPAL detector [10], which is a multipurpose apparatus having nearly 4π steradians acceptance. The central detector (CD) consists of a system of tracking chambers inside a 0.435 Tesla solenoidal magnetic volume. The CD system is surrounded by a time-of-flight (TOF) counter array, a lead glass electromagnetic calorimeter (EC) with a presampler, an instrumented magnet return yoke serving as a hadron calorimeter, four layers of outer muon chambers, and an endcap system which includes a low-angle forward detector (FD). The analysis presented here relies mostly on the EC, CD, and FD systems.

The central tracking detector consists of a precision vertex chamber, a large volume "jet"

chamber, and a chamber for tracking in the $r - \theta$ dimension (the coordinate system is defined with z along the beam axis, and θ and ϕ the polar and azimuthal angles). The main tracking is done with the jet chamber, a drift chamber of approximately four metre length and two metre radius with 159 layers of sense-wires and having 24 sectors in ϕ . The region of tracking registering a minimum of 40 wires covers approximately $|\cos\theta| \leq 0.94$. The time-of-flight system covers the barrel region of $|\cos\theta| \leq 0.82$. It consists of 160 scintillator bars, 6.8 m long and 45 mm thick, located at a radius of 2.4 m. The electromagnetic calorimeter consists of a cylindrical array of 9,440 lead glass blocks of 24.6 radiation lengths thickness covering the range $|\cos\theta| < 0.82$, and 2,264 lead glass blocks of 20 radiation lengths thickness in the endcaps covering the region between $0.81 < |\cos\theta| < 0.98$. Each block subtends a solid angle of approximately $40 \times 40 \text{ mrad}^2$ and projects towards a point near the interaction point in the barrel region and along the beam direction in the endcaps. The two sections of the electromagnetic calorimeter together cover 98% of the solid angle.

The luminosity of the colliding beams was determined by observing small angle Bhabha scattering with the forward detector [11], a lead/scintillator calorimeter at either end of the central detector with an acceptance covering from $40 < \theta < 150 \text{ mrad}$ and 2π in azimuth. At the Z^0 peak the Bhabha cross section in this region is approximately 70 nb. This device currently achieves a systematic accuracy of 5% in the luminosity measurement.

3 The Monte Carlo Generators

To study the process $e^+e^- \rightarrow H^0 Z^{0*} \rightarrow 4 \text{ fermions}$, the decays were modelled using a generator based on the Berends and Kleiss formalism [12] for $e^+e^- \rightarrow H^0 \mu^+ \mu^-$, where initial state radiation is taken into account in first order. This cross section was calculated using the Born cross section [13] incorporating the OPAL measured value of $m_Z = 91.01 \text{ GeV}/c^2$ [11], the corresponding Standard Model value for Γ_Z , and taking into account the effective electro-weak couplings $\alpha(Q^2)$ and $\sin^2\theta_W$ [14] at the Z^0 mass. The more rigorous treatment of initial state radiative corrections via exponentiation was then applied using the formalism described in reference [15]. The theoretical uncertainty on the cross section obtained in this manner is estimated to be $\pm 10\%$. The final state quark fragmentation has been modelled with the LUND [16] (JETSET version 6.3) Monte Carlo (MC). The corrections to H^0 decay due to QCD enhancement of heavy flavour production near threshold have been calculated using references [17]; these are found to be small, and are omitted in the present analysis. The number of H^0 events expected in the data was calculated as a function of m_H and E_{cm} using the Monte Carlos described above. The integrated luminosity at each E_{cm} setting, and the number of predicted H^0 for several hypothetical masses, are shown in Table 1.

The main background processes which have been considered are multihadron and dilepton decays of the Z^0 , as well as two-photon reactions. These backgrounds have been estimated by Monte Carlo techniques. For the multihadronic decays of the Z^0 the LUND MC was used, which describes the OPAL data well, as shown in [18]. For the reaction $Z^0 \rightarrow \tau^+ \tau^-$, the KORALZ [19] generator was used. Simulation of the OPAL detector response to the generated particles was modelled using a Monte Carlo program based on the GEANT [20] package, which provides an accurate description of the response of the various detector components, as demonstrated in [18].

4 Search for $Z^0 \rightarrow \nu\bar{\nu}H^0$, $H^0 \rightarrow q\bar{q}/\tau^+\tau^-$

In the $Z^0 \rightarrow \nu\bar{\nu}H^0$, $H^0 \rightarrow q\bar{q}/\tau^+\tau^-$ channel, the events have mean track multiplicities ranging from 3, for a $3 \text{ GeV}/c^2$ Higgs boson, to 11 for a $20 \text{ GeV}/c^2$ Higgs boson; mean momentum of the Higgs boson decay products is of the order of a few GeV/c over this mass range [21]. As relatively little energy is deposited in the electromagnetic calorimeter in these events, a CD-based trigger has been required in this analysis. A stand-alone track trigger required at least two tracks with $|\cos\theta| < 0.73$, each track having a minimum transverse momentum of $450 \text{ MeV}/c$. The tracks had to be separated by at least 15° in ϕ or have a minimum separation in $\cot\theta$ of approximately 0.36 in order to be resolved by the trigger.

The efficiency of the trigger hardware to detect a single isolated track was measured from the data using $e^+e^- \rightarrow q\bar{q}$ and $e^+e^- \rightarrow e^+e^-$, where both processes are triggered by EC or TOF. The efficiency for single tracks was found to range from 91% for low momentum tracks to 96% for e^+e^- tracks. The measured single track efficiency, including the small dependence on track momentum, was then incorporated in the simulation of the detector response to the Higgs boson signal. Monte Carlo studies demonstrated that, after all the data selection cuts described below were imposed, the track trigger efficiency ranged from 78% for a $3 \text{ GeV}/c^2$ Higgs boson to greater than 98% for $m_H > 10 \text{ GeV}/c^2$. An uncertainty of 4% is ascribed to this modelling of the efficiency.

Information from the trigger and raw data of some detector elements was analyzed by an on-line filter to provide a preliminary selection of the data. Most multihadronic events were eliminated by discarding events having a minimal back-to-back EC energy balance (i.e., an event was rejected if the sum of filter clusters was larger than 4 GeV and there was at least 1 GeV in filter clusters in the hemisphere opposite the highest energy cluster); this is referred to as "cut A". A filter cluster is defined as a group of contiguous lead-glass blocks where the most energetic block had an energy greater than 100 MeV (200 MeV for endcap blocks), and it had at least one neighbouring block having greater than 50 MeV (100 MeV for the endcaps). The remaining events had to pass at least one of the following two conditions (cut B): 1) the event had to contain tracks in at least two jet chamber ϕ sectors and have an azimuthal correlation between a filter cluster in the barrel region and a TOF counter, or 2) the event was required to contain a track in at least one jet chamber ϕ sector, and the sum of all filter clusters (barrel and endcap) had to exceed 2 GeV .

Next, a number of data reconstruction-quality conditions were imposed. Selected events were required to have at least 2 well-reconstructed CD tracks with transverse track momentum larger than $0.5 \text{ GeV}/c$ each, and at least 40 wire-hits per track. Furthermore, all the tracks considered in this analysis were required to have a minimum transverse momentum of $150 \text{ MeV}/c$ and to originate from the interaction point within 2.5 cm in the $r - \phi$ plane, and within $\pm 50 \text{ cm}$ along the beam axis. To reduce the background from two-photon events as well as very forward-going multihadrons, further requirements were imposed, namely that there be less than 2 GeV of energy deposited in the luminosity monitor, and that $|\cos(\theta_{thr})| \leq 0.8$ for the thrust axis of the event. Finally, to reduce the contributions of the leptonic decays of the Z^0 , events containing only two tracks were rejected if the projection of their acolinearity angle in the $r - \phi$ plane satisfied $\cos(\Delta\theta) < -0.85$. To eliminate the effect of small-angle radiative Bhabha scattering, where only a photon conversion is detected in the apparatus, events consisting of only one low-mass e^+e^- pair were eliminated from the sample. The effects of those cuts both in the data and Monte Carlo are shown in Table 2.

To estimate the missing energy and momentum of an event, an algorithm has been developed that makes use of the charged-track and electromagnetic calorimeter information. The algorithm first sums all electromagnetic cluster energies and charged track momenta. A subtraction is then

made for each charged track to correct for double-counting. The amount of energy subtracted is equal to the average energy deposited in the lead glass by charged pions, as a function of their momentum. To demonstrate the method, fig. 1 shows the distribution of p_T , obtained using the algorithm, for a sample of multihadronic Z^0 decays and for LUND MC simulated events. The good agreement between the two demonstrates the reliability of this method to impose cuts on the p_T of the event for the ensuing analysis.

Ordinary multijet events and two-photon reactions are a source of background due to incomplete solid angle coverage by the detector. The two-photon events are a potentially large source of background when $p_T < 3 \text{ GeV}/c$; for p_T larger than this, one of the high-momentum electrons will deposit significant energy in the FD. Figure 2 shows the measured p_T distribution for events satisfying the above cuts. The distribution can be characterized by an accumulation of events in the low- p_T region, and a tail which extends to the high- p_T region. The figure also shows the distribution obtained from a Monte Carlo modelling of multihadronic and dilepton processes, which is in good agreement with the data for $p_T > 4 \text{ GeV}/c$. On the basis of a visual scan of the data, the events with $p_T < 4 \text{ GeV}/c$ have been determined to be mostly beam-gas, beam-wall and two-photon interactions. In the $p_T > 4 \text{ GeV}/c$ region, the data agree with the rates for multihadron and dilepton production predicted by the Monte Carlos, as seen in the last three lines of Table 2. All of these events have been scanned, and all are found to be consistent with the predicted sources, but the scan procedure was not used to select events for the final analysis. For the subsequent analysis, $p_T > 6 \text{ GeV}/c$ has been used as a cut against the backgrounds; the entry corresponding to $p_T > 4 \text{ GeV}/c$ has been included in Table 2 only for the purpose of comparing the effect of the cuts on the data to that on the MC events.

After showing that the high p_T tail is well described by conventional sources, one can impose further cuts to emphasize the asymmetric topology of an H^0 event. This was accomplished by summing all the energy in a 90° (full angle) cone having its axis coincident with the thrust axis of the event, and opening in a direction opposite to the hemisphere containing the maximal energy. The thrust axis was calculated using both CD tracks and EC clusters; this axis has been found to provide a robust test of the asymmetric topology in H^0 events. The distribution of the backward-cone energy (E_{cone}) for the data, after imposing all the previous cuts, is compared in fig. 3 with the expected distribution for a Higgs boson signal of $m_H = 12 \text{ GeV}/c^2$. The final cut on the data is $E_{cone} < 0.5 \text{ GeV}$, which, as shown in the figure, has a minor impact on a Higgs boson signal, but excludes all the measured data. For comparison, the p_T distribution for the data after all cuts except that on p_T is shown in fig. 4, and is compared with that expected for a $12 \text{ GeV}/c^2$ Higgs boson. It can be seen that no candidate is observed in the region where most of the Higgs boson cross section is expected.

5 Search for $Z^0 \rightarrow (e^+e^- \text{ or } \mu^+\mu^-)H^0, H^0 \rightarrow q\bar{q}/\tau^+\tau^-$

The identification of $Z^0 \rightarrow (e^+e^- \text{ or } \mu^+\mu^-)H^0$ for $m_H < 25 \text{ GeV}/c^2$ capitalized on the distinctive signature of two isolated high-momentum tracks. This topology permits one to place on the data extremely conservative cuts which reject the backgrounds while maintaining a high efficiency for Higgs boson events. In the analysis of this channel, cuts A and B were not applied; rather, the two highest-momentum oppositely-charged tracks in the event (henceforth the "major" tracks) were each required to have $p > 10 \text{ GeV}/c$ and the same CD tracking- and vertex-quality cuts as for the previous study. The major tracks also were required to have an opening-angle larger than 90° , and had to be loosely associated with EC clusters in the calorimeter. An EC cluster is defined as a group of contiguous lead-glass blocks where each block registers more than 20 MeV . The associations

were based on the angle between the EC cluster centroid and the CD track, and incorporated the measurement errors on the vectors; this roughly corresponded to an angle of 100 mrad. In order to be associated to a CD track, the cluster energy had to exceed 250 MeV.

Next, an isolation condition was imposed on the major tracks. The total EC energy (less the energy from the associated clusters) in the two cones of full angle 30° centered on the major tracks was required to be less than 5 GeV. Also, the scalar momentum sum of additional tracks in these cones had to be less than 5 GeV/c. Finally, the event had to have at least 4 tracks in addition to the major tracks, separated from them by at least 15° . The efficiency for H^0 to pass all the cuts exceeds 50% for masses above the $c\bar{c}$ threshold; however, no data survive these cuts.

Although there are redundant trigger elements for both the e^+e^- and $\mu^+\mu^-$ channels, the trigger efficiencies have been conservatively evaluated using only the track-trigger in a manner similar to that described for the $\nu\bar{\nu}$ channel; for Higgs boson masses above 3 GeV/ c^2 , it is found to be greater than 98% with a 4% uncertainty after all physics cuts. The probabilities for Higgs boson events to pass the track-trigger and the cuts were obtained in the manner described for the analysis of the $\nu\bar{\nu}$ channel, and are summarized in Table 3.

6 Mass Limits

The number of observable H^0 events predicted by the Monte Carlos in each of the two channels, as a function of m_H , are shown in Table 3 and in fig. 5. Also shown in the figure are the upper limits for observing a signal at the 95% confidence level. A 14% uncertainty on the predicted signal strength was estimated for both search channels by adding in quadrature the uncertainties on the luminosity, cross section calculation, modelling of experimental efficiency, and the trigger efficiency. Since it is not known if the systematic uncertainty is subject to a gaussian distribution, the confidence intervals were estimated by reducing the predicted signal (sum of both channels) by one standard deviation in the systematic error. Thus, the region $3.0 \leq m_H \leq 19.3$ can be excluded at *at least* the 95% confidence level. These limits agree with recent limits published by the ALEPH collaboration [22]; the study presented here extends the range of the mass limit.

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Tables

Table 1: Center of mass energies and integrated luminosity for the data in this analysis. N_H are the predicted numbers of Higgs bosons produced via $Z^0 \rightarrow Z^{0*} H^0$, for all decay channels of the Z^{0*} and H^0 , using the MC described in the text.

E_{cm} (GeV)	$\int \mathcal{L} dt$ (nb ⁻¹)	$N_H, m_H =$ 3 GeV/c ²	$N_H, m_H =$ 20 GeV/c ²
88.28	72	1.75	0.36
89.28	45	2.45	0.46
90.28	90	12.69	2.18
91.00	24	5.47	0.86
91.03	120	28.03	4.37
91.25	1	0.16	0.02
91.28	148	36.43	5.47
91.54	132	32.28	4.66
92.29	59	11.98	1.49
93.25	19	3.25	0.31
93.28	84	14.21	1.34
94.28	12	2.09	0.14
95.03	17	3.07	0.16

Table 2: Effects of cuts on data for the $\nu\bar{\nu}$ search channel. The cuts are described in detail in the text. The events are normalized to 825 nb⁻¹; for cuts 1-6 the data include beam gas and two photon events which are not included in the Monte Carlo modelling.

Cut	QCD MC	$\tau^+\tau^-$ MC	$\mu^+\mu^-$ MC	Data	H^0 of mass 3 GeV/c ²	H^0 of mass 20 GeV/c ²
1) Cuts A,B	173.6	293.0	625.2	5339	22.04	3.60
2) Track trigger	131.8	207.8	459.1	3289	13.92	3.38
3) ≥ 2 good tracks	123.7	206.9	456.5	1648	13.05	3.38
4) Acolinearity cut	123.7	49.6	12.1	868	13.05	3.38
5) $E_{FD} \leq 2.0$ GeV	39.9	49.6	12.1	667	13.05	3.38
6) $ \cos(\theta_{thr}) \leq 0.8$	23.0	48.7	12.1	317	13.05	2.96
7) $p_T \geq 4.0$ GeV/c	23.0	40.0	8.7	70	11.31	2.85
8) $p_T \geq 6.0$ GeV/c	23.0	36.5	6.9	62	10.73	2.70
9) $E_{cone} \leq 0.5$ GeV	0.0	1.0	0.0	0	10.15	2.21

Table 3: Number of predicted events in both search channels, for various Higgs boson masses. The efficiency (ϵ) shown is the total experimental acceptance and detection efficiency. $N_{f\bar{f}}$ is the expected number of observed events after all cuts, and l^+l^- refers to e^+e^- and $\mu^+\mu^-$.

m_H (GeV/c ²)	$\epsilon(\nu\bar{\nu})$	$N_{\nu\bar{\nu}}$	$\epsilon(l^+l^-)$	$N_{l^+l^-}$
3	0.33	10.15	0.36	3.77
5	0.47	10.14	0.50	3.66
7	0.55	9.00	0.60	3.33
10	0.60	6.89	0.64	2.50
12	0.60	5.62	0.66	2.09
14	0.59	4.52	0.67	1.74
16	0.57	3.62	0.66	1.41
18	0.55	2.86	0.66	1.17
20	0.51	2.21	0.65	0.96
22	0.45	1.63	0.65	0.81
25	0.30	0.83	0.62	0.59

Figures

Figure 1. Distribution of p_T , as defined in the text, for a sample of multihadron events in the data. The solid histogram represents the LUND Monte Carlo prediction, as modelled via the detector simulation program. The two datasets are normalized to a common area.

Figure 2. Distribution of p_T for events passing cuts 1-6 (see Table 2). The data are represented by points, while the solid histogram is the Monte Carlo prediction for QCD and dilepton processes.

Figure 3. Distribution of energy in the backward 90° cone after cuts 1-8. The data are represented by points; the solid histogram is the Monte Carlo prediction for a H^0 of mass $12 \text{ GeV}/c^2$.

Figure 4. Distribution of p_T after all cuts (except on p_T). Points represent the data. The Histogram is a Monte Carlo prediction for a H^0 of mass $12 \text{ GeV}/c^2$.

Figure 5. Expected number of events, as a function of the Higgs boson mass, for both search channels. The shaded zone represents the $\pm 1 \sigma_{\text{systematic}}$ level on the predicted number of events. The horizontal line indicates the levels expected for the 95% confidence level upper limit.

Figure 1

Figure 2

Figure 3

Figure 5