Search for Higgs Bosons using the OPAL detector at LEP

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Abstract

Using data from e^+e^- collisions at LEP, recorded by the OPAL detector, a search has been made for evidence of Higgs bosons produced by the reactions $e^+e^- \rightarrow (e^+e^-, \mu^+\mu^-, \nu\bar{\nu},$ or $\tau^+\tau^-) + H^0, H^0 \rightarrow (q\bar{q}$ or $\tau^+\tau^-)$. No candidates were observed in a sample of approximately 8 pb^{-1} of data taken at centre of mass energies between 88.2 and 95.0 GeV. The existence of a Standard Model Higgs boson with mass in the range $3 < m_{\rm H} < 44$ GeV/c^2 is excluded at the 95% confidence level. The same search limits the allowed mass ranges for Higgs bosons predicted by the Minimal Supersymmeteric Model.

1 Introduction

The Standard Model of electroweak interactions[1] requires the existence of one or more scalar particles,the Higgs bosons[2], which have not yet been observed. The minimal Standard Model(MSM) predicts a single Higgs of unspecified mass $m_{\rm H}$ with well-defined couplings to point-like bosons and fermions, which could be produced in e^+e^- collisions in association with a virtual Z^{0*}. The searches presented here exploit the distinctive signatures which result when the Higgs decays into $b\bar{b}, c\bar{c}$ or $\tau^+\tau^-$, while the Z^{0*} decays to $\nu\bar{\nu}, e^+e^-$ or $\mu^+\mu^-$. Masses in the range $0.0 < m_{\rm H} < 0.2$ GeV/c^2 and $3.0 < m_{\rm H} < 25.3$ GeV/c^2 have already been excluded by this experiment in earlier publications[3,4], and to date this and other experiments have excluded the range $0.0 < m_{\rm H} < 41.6$ GeV/c^2 at the 95% confidence level.[3,4,5,6,7,8,9]. Models with 2 Higgs doublets[10] predict more Higgs bosons,including a charged Higgs pair on which this experiment has set mass limits[4]. In the specific case of the minimal Supersymmetric model, only a light scalar h^0 and possibly a CP-odd scalar A^0 would be accessible at LEP 1. Limits on their production have been set by this collaboration in a previous publication[11], and are here extended by applying the MSM search procedure to the channel $e^+e^- \rightarrow Z^0 \rightarrow h^0 Z^{0*}$.

This analysis used data accumulated by the OPAL detector during the 1989 and 1990 scan of the Z^0 resonance. The sample corresponds to an integrated luminosity of $8.0pb^{-1}$, or about 170,000 reconstructed multihadron events.[1]

2 The OPAL detector

OPAL[12] is a versatile apparatus for LEP physics combining good hermeticity and total energy resolution with good lepton identification. It is centred around a system of cylindrical tracking chambers,situated inside a solenoidal coil which provides a magnetic field of 0.435 Tesla. This central detector is surrounded by a time-of-flight counter array and a lead-glass electromagnetic calorimeter with a presampler. Beyond these is an iron magnetic flux return yoke, instrumented to act as a hadron calorimeter , and covered by four layers of muon tracking chambers. The endcap system incorporates a low angle forward detector, which measures luminosity with a systematic error of better than 2.2%[13] using small angle Bhabha scattering. The overall coordinate system is defined with z along the positron beam direction, θ and ϕ being the polar and azimuthal angles.

3 Event Selection and Simulation

Several basic properties were required of each event to ensure that it was well measured, had a high final state multiplicity , and did not originate from a beam-gas or beam-wall interaction. At least five tracks, one with a transverse momentum $p_T >$ 100 MeV/c, were required to originate from the interaction region and to be well-measured by the central tracking chambers. These good tracks had to form more than 20% of the total number.

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[1] $5.2pb^{-1}$ had been analysed before presentation in Singapore

At least five electromagnetic energy clusters were also required; furthermore not more than 2 *Gev* of energy deposit was permitted in the forward detectors. Higgs boson production and decay was simulated[4] using the Berends and Kleiss Monte Carlo[14], incorporating the improved Born approximation[15] and the top quark triangle graph at the $Z^0Z^{0*}H^0$ vertex[16] (leading to a negligible dependence on the top quark mass).The decay branching ratios included QCD corrections[17]. The multihadronic background was simulated using the JETSET7.2 Monte Carlo[18]. Signal and background events were further processed by a program simulating the response of the OPAL detector.

4 Missing Energy Search

In events of the type $e^+e^- \rightarrow Z^{0*}H^0$, $Z^{0*} \rightarrow \nu\bar{\nu}$, $H^0 \rightarrow q\bar{q}$, the invisible final state neutrino energy provides an obvious detection signature. To ensure that events were sufficiently well contained for the missing energy to be adequately measured, and to remove tau pair events, less than 35% of the electromagnetic energy was permitted to be within cones of $|cos\theta| > 0.90$, and the event thrust was required to be less than 0.95. The total 4-momentum of each event was calculated from the measured tracks, and from energy clusters in the electromagnetic and hadron calorimeters,correcting for double counting of charged tracks. This yields a missing momentum vector p_{miss}, which was required to satisfy $|cos\theta_{pmiss}| < 0.90$.

The mass distribution of the remaining events, normalised to the centre-of-mass energy, showed that most were due to multihadronic decays of the Z^0. Apart from some two-photon contribution at low mass, this mass distribution was well reproduced by the multihadron Monte-Carlo simulation. In order to suppress the multihadron background and exploit the acollinear topology of the $\nu\bar{\nu}H^0$ final state, events were divided into two hemispheres and the 4-momentum of each half summed as previously described. For all events with energy > 3 *GeV* in each hemisphere, the momentum vectors of the two hemispheres were required to be acollinear ($> 26^o$) and acoplanar ($> 16^o$). This effectively removed most two-jet events. Two-photon events were eliminated by requiring that the total transverse momentum with respect to the beam axis exceeded 6 GeV/c. Next the missing energy signature was emphasised by requiring that the summed track momenta and cluster energies within 30^o of the missing momentum vector be less than 2 *GeV*. This eliminated mis-matched multi-jets and heavy flavour decays. No events remained with a normalised mass below 0.62, which is already incompatible with $m_H \leq 50\ GeV/c^2$. However to retain sensitivity to higher masses, no mass cut was applied. The remaining high mass events (mostly asymmetric three- and four- jet types) also had high masses in at least one hemisphere, in contrast with the low mass heavy quark jets expected from Higgs boson decay. They were all removed by requiring either that the average mass of the two hemispheres was less than 12.5 GeV/c^2 (consistent with b-quark jets), or that the lower of the two hemisphere energies be less than 3 *GeV* (consistent with a monojet). The overall efficiency of this selection for detecting a simulated Higgs boson of mass 40 GeV/c^2 in the missing energy channel was 59%.

5 Search for Isolated Lepton Pairs

After the same general selection cuts, a search was made for events of the type $Z^0 \rightarrow (e^+e^-$ or $\mu^+\mu^-) + H^0$. Pairs of well-measured, oppositely charge lepton candidates were selected, with opening angle $> 30^o$ and with each track having a momentum $> 5\ GeV/c$. The lepton selection criteria demanded that the candidate track had appropriate associated energy or hit patterns in the electromagnetic and hadron calorimeters. In addition, the summed electromagnetic energy of an e^+e^- pair or the summed scalar momentum of a $\mu^+\mu^-$ pair was required to exceed 25 GeV/c.

Events were accepted if the two leptons were both isolated, with less than 5 *GeV* each of corrected electromagnetic, charged or hadronic calorimeter energy within 30^o around each track. To allow for asymmetric Z^{0*} decays, events were also accepted if the same condition was satisfied for cones of half-angle 45^o and 15^o, providing the lepton in the 45^o cone had an energy exceeding 20 *GeV*, and that there was less than 1 *Gev* of unassociated energy accompanying the lepton in the 15^o cone.

This selection eliminated all events, but extensive background studies suggested requiring less than 1 GeV/c^2 of charged momentum within 15^o of each lepton, to make future analysis more robust. The overall efficiency of the complete selection for detecting a 40 GeV/c^2 Higgs boson in the isolated lepton pair channel is 53%.

6 Search for $Z^0 \rightarrow \tau^+\tau^-$ jet jet

To obtain a clear signature for this channel, high sphericity ($S > 0.1$) events with more than seven charged tracks were required to contain two isolated oppositely charged tracks from the single prong decays of the $\tau^+\tau^-$. Multi-jet events were rejected by requiring each isolated track to have momentum greater than 3 GeV/c, to be more than 30^o from any other track and to have no more than 0.5 GeV of electromagnetic energy within a 15^o to 30^o annular region surrounding it. The 30^o isolation cones were required to be fully contained within the fiducial region, which implies track polar angles restricted to the range $45^o < \theta < 135^o$. 186 events remained, for each of which the mass of the pair was less than 7.5 GeV/c^2. Requiring a minimum pair mass of 10.0 GeV/c^2 gave an overall efficiency for this selction of 5% for $H^0 \rightarrow \tau^+\tau^-$ and 8% for $Z^{0*} \rightarrow \tau^+\tau^-$, assuming a Higgs boson mass of 40 GeV/c^2.

7 Systematic Uncertainties and Mass Limits

The errors due to luminosity measurement (2.2%) and Higgs boson cross-section (2%) were common to all the analyses.

For the missing energy channel,the charged multiplicity cut introduced a sytematic error of 1.6%, due to B decay modelling uncertainties. A 2% uncertainty was attributed to fragmentation dependence based on studying the acceptance change as fragmentation and QCD parameters were varied. Imperfect simulation of the calorimeter response introduced a further 3% systematic error.

For the di-lepton search, the sytematic errors came from uncertainties in the simulation of final state radiation (1%) and of the detector response to isolated leptons (4%).

Both the above searches therefore had a combined systematic error of 5%. For the $Z^0 \rightarrow \tau^+\tau^-$ jet jet channel, which made a relatively small contribution to the final mass limit, a 10% systematic uncertainty was estimated[4]. The expected numbers of observed events, reduced by their respective systematic errors, are shown in Fig 1, as a function of Higgs boson mass, for each channel separately and for the combination of all channels.

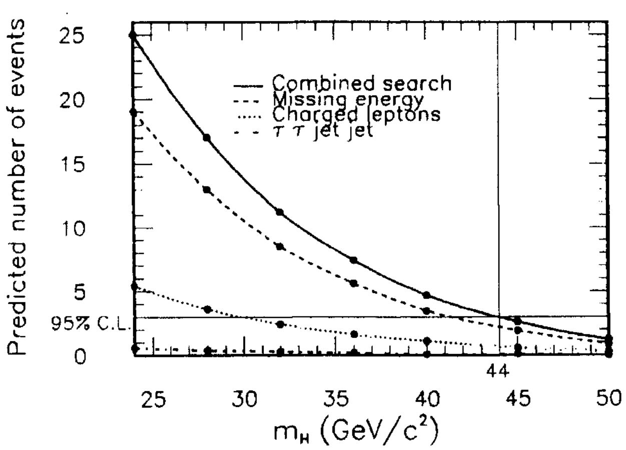

Figure 1: Expected Number of Events as a Function of the Higgs Boson Mass

A minimal standard model Higgs boson is excluded for $m_H < 44$ GeV/c^2 at the 95% confidence level.

Applying the null result to the search for the light supersymmetric Higgs scalar h^0 yields an excluded region in the plane defined by the mass of the h^0 and the ratio $tan\beta$ of the vacuum expectation values of the two Higgs doublets. This is shown in Fig. 2, which incorporates results from our previous publications[3,4].

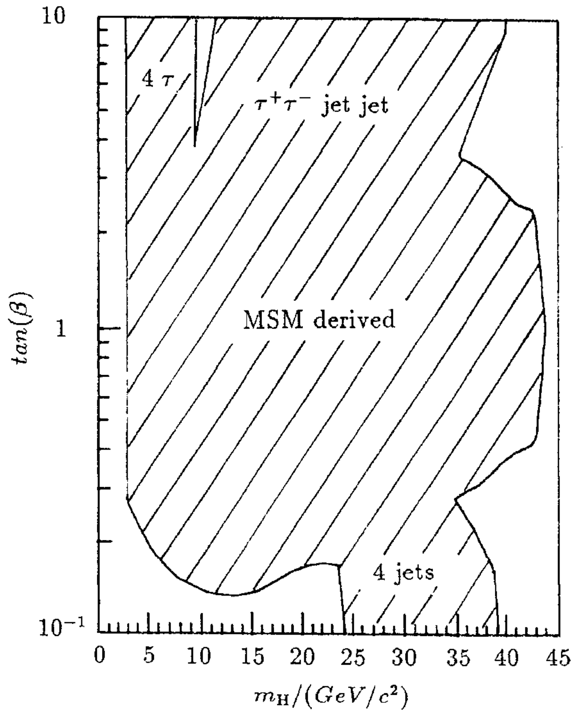

Figure 2: Excluded Region in the $m_H - tan\beta$ plane for MSSM Higgs Boson

8 Conclusion

The existence of a minimal Standard Model Higgs boson has been excluded at the 95% confidence level in the mass range $3 < m_H < 44\,GeV/c^2$. Limits on the existence of minimal supersymmetric Higgs bosons have been extended. The searches were limited by available statistics and should remain sensitive for higher Higgs masses as the OPAL experiment collects more data.

9 Acknowledgements

I would like to thank the conference organisers for their hospitality and efficiency. It is a pleasure for OPAL to thank CERN SL Division for the smooth operation of the LEP accelerator, precise information on the absolute energy, and their continuing close cooperation with our experimental group. In addition to the support staff at the collaborating institutions, we are pleased to acknowledge: Department of Energy,USA, National Science Foundation,USA, Science and Engineering Research Council,UK, Natural Sciences and Engineering Research Council,Canada, Israeli Ministry of Science, Minerva Gesellschaft, The Japanese Ministry of Education,Science and Culture (the Monbusho) and a grant under the Monbusho International Science Research Program, American Israeli Bi-national Science Foundation, Direction des Sciences de la Matière du Commissariat a l'Energie Atomique,France, The Bundesministerium für Forschung und Technologie,FRG, and the A.P Sloan Foundation.

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