UNIVERSITÄT BONN
Physikalisches Institut

Higgs Particle Searches with the OPAL Detector at LEP

K. Desch
Physikalisches Institut der Universität Bonn

Searches for Higgs bosons in the framework of the Standard Model (SM) and the Minimal Supersymmetric Standard Model (MSSM) are presented based on data of the OPAL experiment at LEP. The data were taken at centre-of-mass energies between 130 and 172 GeV. Some experimental issues in the different search channels are described and lower mass limits for the Standard Model Higgs boson H and for the neutral and charged MSSM Higgs bosons are given. For the MSSM mass contraints on the allowed parameter space are given. The prospects for Higgs searches at LEP 2 in the near future are shortly discussed.

*Work supported by the German Ministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF) under contract no. 05 $7BN$ 18P 0

Post address:
Nussallee 12
D-53115 Bonn
Germany

BONN-HE-97-08
Bonn University
December 1997
ISSN-0172-8733

HIGGS PARTICLE SEARCHES WITH THE OPAL DETECTOR AT LEP

K. DESCH

Physikalisches Institut der Universität Bonn, Nussallee 12, D-53115 Bonn, Germany, E-mail: Klaus.Desch@cern.ch

Searches for Higgs bosons in the framework of the Standard Model (SM) and the Minimal Supersymmetric Standard Model (MSSM) are presented based on data of the OPAL experiment at LEP. The data were taken at centre-of-mass energies between 130 and 172 GeV. Some experimental issues in the different search channels are described and lower mass limits for the Standard Model Higgs boson H and for the neutral and charged MSSM Higgs bosons are given. For the MSSM mass contraints on the allowed parameter space are given. The prospects for Higgs searches at LEP 2 in the near future are shortly discussed.

1 Introduction

In the Standard Model the Higgs mechanism allows the particles to acquire masses while through spontaneous symmetry breaking the underlying gauge theory remains renormalizable. As a consequence a complex scalar field doublet has to be introduced giving rise to one physical scalar particle, the Higgs boson. Many models beyond the Standard Model also predict one or more Higgs bosons, the Minimal Supersymmetric Standard Model (MSSM) being the most prominent. In the MSSM two complex scalar field doublets give rise to five Higgs bosons, three being neutral (h, H, A) and two charged (H^+, H^-). An overview on Higgs physics at LEP 2 is given in ref. 1.

Since 1995 the energy of LEP has been increased in steps up to 184 GeV in 1997. This increase opens the possibility to search for Higgs bosons in a previously unaccessible mass range. In this contribution, partly preliminary results are reported from searches at centre-of-mass energies between 130 GeV and 172 GeV. The analyses are based on integrated luminosities of 5.2 pb^{-1} at 130-136 GeV, 10.0 pb^{-1} at 161 GeV and 10.4 pb^{-1} at 170-172 GeV.

The OPAL detector with its acceptance of nearly 4π solid angle and its good tracking, calorimetry and particle identification capabilities is well suited for Higgs searches which involve a large variety of different final states. The identification of b-flavoured hadrons plays a major rôle in the identification of neutral Higgs bosons, since they decay predominantly into a pair of b-quarks. To tag b-flavour the upgraded Silicon microvertex detector of OPAL is of essential benefit. This detector, consisting of two layers of double sided Silicon micro-strip detectors has a spatial resolution of 5 μm (12 μm) in the azimuthal (longitudinal) coordinate. It is located at radial distances of 6 and 7.5 cm from the interaction point. Secondary vertices from long-lived b-hadrons can be reconstructed with high spatial resolution.

2 Search for the Standard Model Higgs Boson

The most prominent production process for the Standard Model Higgs Boson is the Bjorken process $e^+e^- \to HZ$ while the WW- and ZZ-fusion processes $e^+e^- \to He^+(\nu_e)e^-(\bar{\nu}_e)$ have very small cross section and are only relevant when the Bjorken process is kinematically forbidden. The final states in which the searches for the Higgs boson are performed are characterised by the decay of the associated Z boson. They are

- Four jet channel: $HZ \to b\bar{b}q\bar{q}$. This channel has the largest branching fraction of approximately 60%. The selection makes use of both kinematical information from the 4 reconstructed jets including kinematical fitting constraining total energy, total momentum and the invariant mass of one jet-pair to m_Z and of tagging of b-flavour in the jets which are associated to the Higgs boson. A recent improvement in this analysis has been the use of a likelihood discriminant to separate signal from background instead of a traditional sequence of cuts in the separating variables. No candidate events are observed in the OPAL data at $\sqrt{s} = 161$ GeV and one candidate event is observed at $\sqrt{s} \approx 171$ GeV while 0.75 (0.88) are expected from standard model background processes. The efficiency of the selection for Higgs signal events is around 30% for a wide range of Higgs masses in the interesting region. The observed candidate event has a reconstructed invariant mass of 75.6 ± 3.0 GeV for the two jets associated with the Higgs boson and shows strong signs of b-flavour while it is kinematically consistent with W^+W^- production.

- Missing energy channel: $HZ \to b\bar{b}\nu\bar{\nu}$. This channel has a branching fraction of approximately 18%. It is characterized by two acoplanar jets carrying b-flavour from the Higgs decay and missing energy and momentum transverse to the beam direction due to the undetected neutrinos from the Z-decay. The dominant backgrounds are mismeasured $Z/\gamma^* \to q\bar{q}$ events and four-fermion processes with neutrinos in the final state such as $W^+W^- \to l^\pm\nu q\bar{q}$ with the charged lepton escaping detection. The selection makes use of the fact that for most backgrounds the missing momentum vector points close to the beam direction. Furthermore the missing mass is close to m_Z for signal events. Events with identified charged leptons are discarded. Finally, the jets are required to show signs of b-flavour. The efficiency for signal events is between 42 % and 47 % depending on the assumed Higgs mass. 0.55 (0.9) background events are expected at $\sqrt{s} = 171(161)$ GeV. One event is observed at $\sqrt{s} = 161$ GeV with a visible mass of 39.3 ± 4.9 GeV consistent with background expectations.

- Tau channels: the two processes (A) $HZ \rightarrow q\bar{q}\tau^+\tau^-$ and (B) $HZ \rightarrow \tau^+\tau^- q\bar{q}$ have total branching fraction of approximately 9 %. The analysis is sensitive to both processes. They are characterised by a pair of tau leptons and a pair of energetic hadronic jets. Either the jet pair or the tau lepton pair should have an invariant mass consistent with the mass of the Z boson. Tau leptons are identified through their most prominent decay products: electrons, muons, or isolated narrow jets with one or three charged particles adding up to unit charge. After identifying tau candidates, the rest of the event is forced into two jets whose properties are used to further reduce the background. The efficiency is 20% - 30% for process (A) and 16% - 22 % for process (B) for Higgs masses between 50 and 70 GeV. The total expected background is 0.59 (0.16) events at $\sqrt{s} = 171(161)$ GeV. No candidates are observed.

- Lepton channels: the process $HZ \rightarrow e^+(\mu^+)e^-(\mu^-)q\bar{q}$ has only a branching fraction of approximately 6 % but provides the cleanest signature for signal events and thus has the highest efficiency at very low background levels. The selection requires two isolated oppositely charged leptons with invariant mass yielding m_Z. The selection efficiency is between 60% (70%) and 65% (71%) for electrons (muons) with a total expected background of 0.14 (0.04) events at $\sqrt{s} = 171(161)$ GeV. No candidates are observed.

Since no excess of events over the expected background is observed a limit on the mass of the standard model Higgs boson can be derived. A method [4] which takes into account the experimental mass resolution for candidate events in the different search channels as well as the mass distribution of the background was adopted. A limit of 69.4 GeV at 95% confidence level is obtained. Figure 1 shows the expected number of signal events together with the experimental 95% confidence level upper limit for a possible Higgs boson signal in the presence of candidate events as a function of the assumed Higgs boson mass.

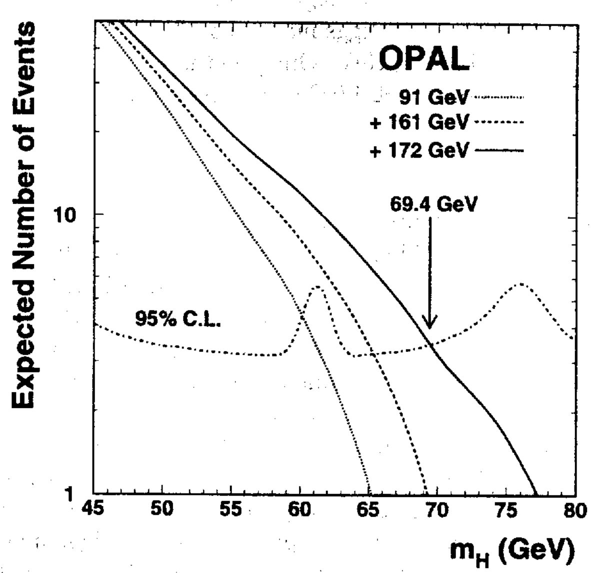

Figure 1: Expected number of events as a function of the Higgs boson mass. OPAL searches at $\sqrt{s}=m_{Z^0}$ (dotted), including $\sqrt{s}$=161 GeV(dashed) and the grand total (full line) including OPAL searches at $\sqrt{s}$=170/172 GeV. The dash-dotted horizontal line is the 95% confidence level upper limit for a possible Higgs boson signal in the presence of the observed high-mass candidate events (see text). The intersection of the solid curve with the dash-dotted curve, indicated by the arrow, determines the 95% confidence level lower limit obtained for the Higgs boson mass;

3 Search for MSSM Higgs Bosons

An appealing feature of the MSSM is its ability to make precise predictions for production cross sections and decay branching fractions for Higgs boson production once the model's free parameters are fixed. This enables the experimental searches to set limits on the possible parameter space of the model.

3.1 Neutral Higgs Bosons

In the neutral Higgs sector of the MSSM three Higgs bosons are predicted, the lighter h and the heavier H being CP-even and A being CP-odd. The h boson can be produced in the same process as the Standard Model Higgs boson ($e^+e^- \to HZ$). Furthermore in the MSSM there exists the pair production process of h and A: $e^+e^- \to h\,A$. These two processes show a complementarity in their cross sections: while at tree level the cross section for the Bjorken process is proportional to $\sin^2(\beta - \alpha)$, the pair production cross section is proportional to $\cos^2(\beta - \alpha)$. Thus, in regions where one process is suppressed, the other is enhanced. While for large regions of the MSSM parameter space both h and A predominantly decay into $b\bar{b}$, in some regions the decays into $\tau^+\tau^-$, $c\bar{c}$ or even gg become important. Furthermore, if kinematically possible also the decay into a pairs of supersymmetric particles, e.g. into neutralinos $\chi_0^1\chi_0^1$ is possible, giving rise to invisible Higgs decays.

The preliminary OPAL search is performed in the channels (1) $e^+e^- \rightarrow hZ$ and (2) $e^+e^- \rightarrow hA$. For the channel (1) the search for the Standard Model Higgs boson is adopted and the search results are reinterpreted for the MSSM process. For channel (2) searches in two different final states are performed: $hA \rightarrow b\bar{b}b\bar{b}$ and $hA \rightarrow q\bar{q}\tau^+\tau^-$. In the case when $m_h > 2m_A$ the decay $h \rightarrow AA$ is possible. This leads to additional final states. The most relevant channels $hZ \rightarrow b\bar{b}b\bar{b}q\bar{q}$ and $hA \rightarrow b\bar{b}b\bar{b}b\bar{b}$ are accounted for by dedicated searches. The dedicated searches which have not already been described in the Standard Model section are shortly described in the following:

- $e^+e^- \rightarrow hA \rightarrow b\bar{b}b\bar{b}$: this channel is characterised by the presence of 4 energetic jets all containing b-flavour. A cut based analysis is applied. In a first step clear four jet final states are selected. Then b-tagging using the Silicon microvertex detector is applied on each of the four jets. The efficiency of the selection for $m_h = m_A = 55\,\text{GeV}$ is between 37% and 42% depending on the centre-of-mass energy with a total expected background of 3.6 events. Three events are observed. These events are not clustering in the (m_h, m_A) plane.

- $e^+e^- \rightarrow hA \rightarrow \tau^+\tau^-q\bar{q}$: this signal has signature which is very similar to that of the Standard Model τ-channel except for both dijet masses being unconstrained. The efficiency for $m_h = m_A = 55\,\text{GeV}$ is 46%. Five events are observed in the data with 3.8 events expected from Standard Model background processes. None of the candidate events is close to the $m_h = h_A$ diagonal.

A statistical method [4] has been used to combine the many different search channels. For each set of MSSM parameters the production cross section and the decay branching ratios are calculated. Each point in the parameter space is separately excluded at 95 % confidence level or not.

We assume the Higgs sector in the MSSM to be uniquely defined by a set of seven parameters: (a) the mass m_0 of the sfermions at the grand unification (GUT) scale; we assume unification of these masses at the GUT scale. The

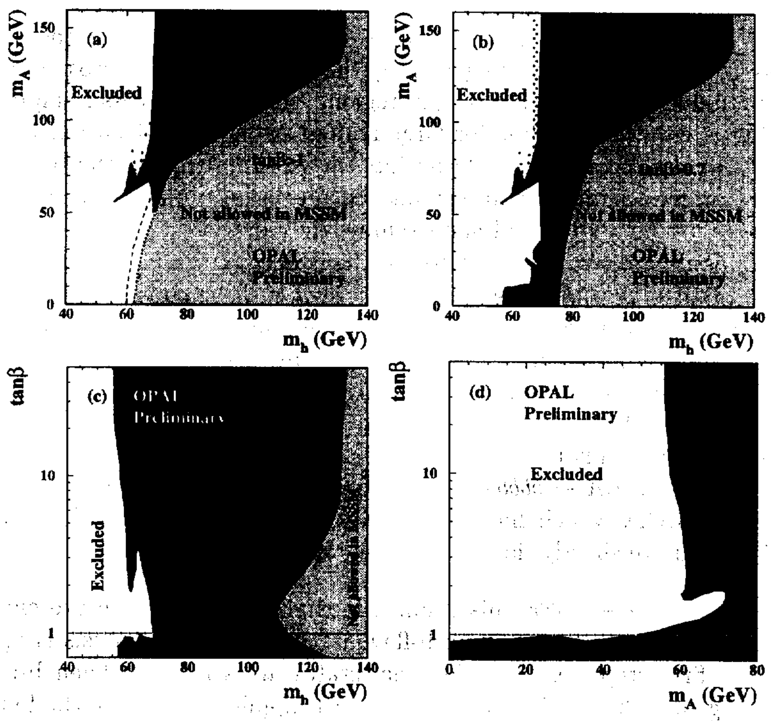

Figure 2: Exclusion limits for case (B), the benchmark scans. (a) Exclusion limit in the (m_h,m_A) plane for $\tan\beta>1$. The dark area cannot be excluded. The upper bound on the unexcluded dark area corresponds to maximal mixing. The dashed line indicates the same upper bound for minimal mixing. (b) As (a) but for $\tan\beta>0.7$. (c) Exclusion limit in the (m_h,$\tan\beta$) plane. (d) Exclusion limit in the (m_A,$\tan\beta$) plane. The entire plane is theoretically allowed for both minimal and maximal mixing.

physical sfermion masses are obtained by running m_0 down to the electroweak scale through the relevant renormalization group equations; (b) the SU(2) gaugino mass term M_2 at the GUT scale. The U(1) and SU(3) masses M_1 and M_3 are calculated from M_2 using the ratio of the coupling constants, $M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3$; (c) the scalar-fermion tri-linear couplings A; (d) the Higgs mass mixing term μ; (e) the (running) mass of the CP-odd Higgs boson m_A; (f) the ratio of the vacuum expectation values of the two Higgs field doublets, $\tan\beta$; (g) the mass of the top quark m_t. Although the top mass is measured, its variation within approximately two standard deviations around its measured value still has significant impact of the MSSM Higgs phenomenology through the m_t^4 dependence of the loop corrections to m_h.

Three different scans of these parameters are performed: A general scan with all parameters varying freely and two 'benchmark scans' corresponding to minimal (maximal) stop mixing giving rise to small (large) loop corrections to m_h. These parameter scans are defined by $\mu = -0.1 m_Q, A = 0$ for minimal mixing and $\mu = -0.1\, m_Q$, $A = \sqrt{6}\, m_Q$ for maximal mixing. Here m_Q is the physical mass of the 'left-up' squark, which is calculated from m_0. All other parameters vary as in the general scan.

Figure 2 shows excluded and unexcluded areas in the three parameter planes (m_h,m_A), (m_h, $\tan\beta$) and (m_A, $\tan\beta$) for the benchmark scans. A mass m_h below 55.9 GeV is excluded at 95% C.L. for any value of m_A. In the case of minimal (maximal) mixing, the limit on m_A is 56.0 (50.6) GeV for $\tan\beta > 1$. However if the requirement on $\tan\beta$ is relaxed to $\tan\beta < 0.7$, no limit on m_A can be derived.

In the general scan, the overall behaviour is the same as in the benchmark scans. However, scattered unexcluded points at values of m_h below the exclusion line in the benchmark scans occur. These points typically have very low values for $\sin^2(\beta - \alpha)$ and a large mass difference $|m_h - m_A|$. Thus the hZ production is suppressed while the cross section for hA production is too small to be excluded at current integrated luminosity.

3.2 Charged Higgs Bosons

In the MSSM at tree level, charged Higgs bosons are predicted to be heavier than the W bosons. Radiative corrections do not change this prediction significantly. Therefore a discovery of a charged Higgs boson lighter than the W boson would put strong constraints on the MSSM parameter space.

In the preliminary OPAL analysis of LEP 2 data for centre-of-mass energies between 130 GeV and 172 GeV it is assumed that the charged Higgs decays into either $\tau\nu_\tau$ or $q\bar{q}$. Since the branching fraction in either of these two final states is model dependent, limits on the charged Higgs mass are given as a function of BR($H^+ \to \tau^+\nu_\tau$). Since charged Higgses would be predominantly pair-produced via the process $e^+e^- \to H^+H^-$, the three final states $q\bar{q}q\bar{q}$, $q\bar{q}\tau\nu_\tau$ and $\tau\nu_\tau\tau\nu_\tau$ are investigated. No excess over the expected background from Standard Model processes is observed. An absolute lower limit of 52.0 GeV at 95% C.L. for the mass of the charged Higgs boson can be given. In figure 3 the mass limit is shown as a function of BR($H^+ \to \tau\nu_\tau$).

4 Further Prospects for Higgs Searches at LEP 2

In 1997, LEP has delivered an integrated Luminosity of more than 55 pb^{-1} at $\sqrt{s} = 183\,\text{GeV}$ to each of the four experiments. These data are currently being

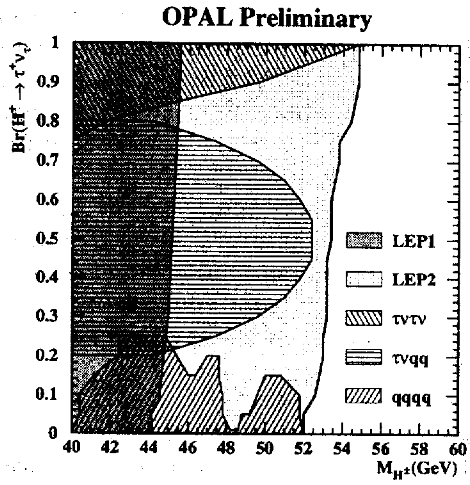

Figure 3: Charged Higgs boson: excluded areas at 95% C.L. in the ($m_H^{\pm}$,BR($H^+ \to \tau\nu_\tau$))-plane. The dark shaded area is excluded by LEP1 and the light shaded area by the LEP2 searches up to 172 GeV centre-of-mass energy. The differently hatched areas show the excluded regions by the individual search channels.

analysed. If no signal is found, the mass limit on the Standard Model Higgs boson is going to rise above 80 GeV. In the remaining years of LEP 2 running OPAL has the chance to either discover or exclude the Standard Model Higgs up to a mass of close to 100 GeV, depending on the final LEP 2 energy and the integrated luminosity. For the MSSM, if no signal is discovered, there is a good chance to rule out low $\tan\beta$ solutions completely.

References

1. E. Accomando *et al.* in *Physics at LEP 2* (CERN 96-01 , 1988, p. 351).
2. The OPAL Collaboration, K. Ackerstaff *et al.*, *Phys. Lett.* B **391**, 210 (1997).
3. The OPAL Collaboration, K. Ackerstaff *et al.*, CERN-PPE/97-115, accepted by *Z. Phys.* C.
4. P. Bock, *Determination of exclusion limits for particle production using different decay channels with different efficiencies, mass resolutions and backgrounds*, Heidelberg Institute Preprint HD-PY96–05 (1996), OPAL IP059 (1997).