SM Higgs Boson Hunting at LEP

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Abstract

The best Higgs hunting machine ever built, LEP, started operation in the summer of 1989. Since then the mass region explored in searching for the Standard Model Higgs Boson has been extended by more than an order of magnitude. An overview of the searches performed by the four LEP Collaborations by the end of 1991 is presented.

Submitted to the International Journal of Modern Physics A
1 Introduction

The acceptance of the so-called Standard Model (SM) [1] of Particle Physics has grown significantly during the last decade. Impressive amounts of data from different kinds of experiments have provided increasing support to this theory. In addition, all searches and precision measurements aimed to test its validity have only proven its excellent experimental health. Nevertheless, two particles predicted by the SM have not yet been observed. The sixth quark called top, and the Higgs Boson ($H^0$). According to recent experimental results [2] the top quark should have a mass between 100 and 200 GeV/c^2, and will probably be detected in the present or next generation of hadron colliders. The existence of the second unobserved particle in the SM is somehow more subtle, since it appears in the theory through a mathematical and rather artificial trick. The Higgs Boson has its origin in the so-called Spontaneous Symmetry Breaking mechanism [3], which is necessary to provide mass to the Intermediate Weak Bosons ($W^\pm$, $Z^0$). Since the $W^\pm$ and $Z^0$ are known from experiment to be massive, the Higgs mechanism, rather than being a cosmetic detail in the theory, appears to be indispensable. The theory provides a precise value for the Intermediate Bosons masses, but unfortunately the mass of the Higgs Boson is not predicted. Nevertheless some indirect weak limits can be deduced from purely theoretical considerations [4]. In addition some constraints can be obtained from precision measurements but these depend heavily on the top mass [5]. Hence a very large mass region is available for the Higgs.

In this paper a review of the searches for a SM Higgs Boson at LEP is presented. The structure of the paper is as follows:

Some properties of the Higgs Boson and its decay modes are summarized in section 2. The general procedure to derive such limits is explained in section 3. The hunt for the Higgs Boson prior to LEP is summarized in section 4. The null results of these searches led to lower limits on the Higgs Boson mass. Some of the resulting limits suffered from theoretical uncertainties in the cross section of the processes involved. The large and well understood HZZ coupling has turned LEP into the best place to search for the Higgs Boson. Its production at LEP is discussed in section 5. A description of the various search channels is given in section 6. The results obtained by the various LEP experiments are compared in section 7. A pedagogical exercise of combining all the results and deriving a lower limit on the Higgs Boson mass, based on all the data collected at LEP by the end of 1991, follows. Section 8 summarizes the Higgs history at LEP and extrapolates into the future at $\sqrt{s} = m_{Z^0}$ (LEP 100). A flavour of Higgs searches with a center-of-mass energy around the $W^+W^-$ threshold of 170-200 GeV, at LEP 200, is given in section 9.
2 Decay of the Higgs Boson

The Higgs coupling to fermions is responsible for the generation of the fermion masses. It is given by

\[ g_{H^0 ff} = \frac{g}{2M_W} m_f \]  

(1)

where \( g \) is the electroweak coupling constant. From this it can be deduced that the branching-ratio of the Higgs to fermions is also proportional to their mass squared via

\[ BR(H^0 \to f \bar{f}) = \frac{N_c m_f^2 \beta_f^3}{\sum_f N_c m_f^2 \beta_f^3} \]  

(2)

where \( N_c \) is the number of colours and \( \beta_f = \sqrt{1 - \frac{4m_f^2}{m_W^2}} \) is the fermion velocity in the Higgs Boson rest frame. This tree-level approach to the Higgs Boson decay widths has to be slightly changed due to QCD effects.

The \( O(a_s) \) QCD corrections to the hadronic decay of a Higgs Boson have been calculated by various authors [6]. The effect of these corrections is significant near thresholds where bound states can be formed and a mixing of the Higgs Boson with quarkonium states might occur. Outside the resonance regions these corrections are very small as can be seen in Figure 1, where the branching ratio \( BR(H^0 \to b \bar{b}) \) is shown (outside the resonance region) with (dashed) and without (solid) QCD first order corrections. As can be observed, QCD corrections always enhance the decay of the Higgs Boson to bottom quarks.

Special care is needed when the Higgs Boson mass is above the pion-pair threshold and below 2-3 GeV/c².

Figure 1: \( BR(H^0 \to b \bar{b}) \) as a function of the Higgs Boson mass, with (dashed) and without (solid) QCD first order corrections.

Figure 2: A light Higgs Boson decaying via a heavy fermion loop.

In this mass range the decay is dominated by a triangle diagram with intermediate heavy quarks, leading to a two gluon final state shown in Figure 2.

For example, a Higgs Boson lighter than 1 GeV/c² can decay into either a pair of muons or a pair of pions. Since the Higgs Boson couples to the current
mass of the quarks the muonic mode would naively be expected to dominate. However, the heavy quark loop in the two gluon channel enhances the pionic branching ratio considerably. Explicit calculations by Voloshin [7] using QCD low-energy theorems show that below the $\rho \rho$ threshold ($\sim 1.4$ GeV$/c^2$) the decay of a light Higgs Boson is dominated by two body final states. However, the extension of these calculations to higher masses is doubtful, as the validity of low energy QCD theorems in this mass range is questionable [5b, 7, 8].

Furthermore, even the results below 1 GeV$/c^2$ are subject to controversy. Raby and West [9] claim that if $I=0$, $J^{PC} = 0^{++}$ $\pi \pi$ resonances are taken into account the decay into hadronic final states is significantly enhanced. As a consequence the branching ratio $BR(H^0 \rightarrow \mu^+ \mu^-)$ decreases by an order of magnitude in the mass range $2m_\pi < m_{H^0} < 2m_K$. Figure 3 shows the branching ratios into di-muons obtained by Voloshin as well as that obtained by Raby-West.

As can be seen, while the branching ratio for a Higgs Boson into muons according to Voloshin is above 20% for masses below 1 GeV$/c^2$, a value of ~1% is obtained when the Raby and West correction is taken into account.

Given the uncertainty of the theoretical prediction for $2m_\pi < m_{H^0} < 2m_K$ and the fact that the above calculations rely on low energy QCD theorems, of debatable validity above 1 GeV$/c^2$, it is clear that the calculations of the Higgs Boson partial widths for $m_{H^0} < 2 - 3$ GeV$/c^2$ suffer from significant model dependence.

To summarize, since the Higgs Boson couples to mass, it tends to decay to the heaviest particle-antiparticle pair kinematically allowed. This behavior is illustrated in Figure 4 (from [4]) where the Higgs width into different particles is shown versus $m_{H^0}$.

As can be observed, in the mass region below the $\mu \mu$ threshold only two possible decay modes are allowed: $H^0 \rightarrow e^+e^-, \gamma\gamma$. In the region

$$2\mu < m_{H^0} < 10 \text{ GeV}/c^2$$

many other decay channels open as the mass increases and the theoretical situation becomes confused due to hadronic effects. For $m_{H^0} > 10$ GeV the Higgs Boson decays predominantly into a $b\bar{b}$ quark pair ($\approx 87\%$), with a small fraction going into charm ($\approx 7\%$) and tau ($\approx 6\%$) pairs.
Figure 4: The approximate partial decay widths of $H^0$ to all two body partonic decay modes.

3 How to derive a Limit

If no clear signature indicating the discovery of the Higgs Boson is found in a given data set, the extraction of a lower limit on its mass can be performed. The basic procedure of deriving such a limit (at the 95% and 99% Confidence Level) is presented in this section. The application of this procedure in presence of candidate events with known mass will be introduced in section 7.

The number of expected Higgs Boson events with mass $m_{H^0}$ and cross section $\sigma(m_{H^0})$ is given by

$$N_{\text{expected}}(m_{H^0}) = \int \mathcal{L} \cdot \sigma(m_{H^0}) \cdot \epsilon(m_{H^0})$$

(3)

where $\mathcal{L}$ and $\epsilon(m_{H^0})$ stand for the integrated luminosity and for the detection efficiency respectively.

The recipe given in the Particle Data Group [10] based on the Poisson distribution is used to derive the lower limit on the Higgs Boson mass. This recipe indicates that if no events are observed and at least $3(4.6)$ Higgs Boson events are expected at a given mass $m_{H^0}$, then a Higgs Boson with this mass can be excluded at the 95(99)% Confidence Level (CL). However, if one event is observed and conservatively taken as a candidate, but at least $N_{\text{exp}}(m_{H^0}) > 4.8(6.6)$ Higgs Boson events are expected, a $H^0$ with mass $m_{H^0}$ can still be excluded at the 95(99)% CL.

Table 1 summarizes the number of expected Higgs events, $N_{\text{exp}}(m_{H^0})$, necessary to set 95% and 99% CL limits, if $N_{\text{obs}}$ candidates are observed.

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<th>$N_{\text{obs}}$</th>
<th>$N_{\text{expected}}$</th>
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Table 1: The number of Higgs Boson events expected in order to exclude a Higgs at the 95% and the 99% Confidence Level, when $N_{\text{obs}}$ events are conservatively taken as Higgs candidates.
4 The Higgs Search Prior to LEP

Many limits have been derived using various methods and experiments. Unfortunately most of them have been obtained based on theoretical predictions with some uncertainties in the Higgs Boson production or decay branching ratios, due mainly to hadronic effects. Below, only some of these limits (at the 90% CL or more) are listed. Comprehensive reviews can be found in [4, 8].

- **Muonic atoms:**
  Muonic x-rays provided a limit extending to arbitrarily small masses. The existence of a light boson would imply additional muon-nucleon interactions in muonic atoms. High precision transition measurements were carried out in those atoms in order to seek for anomalous effects. The experiment found agreement with theoretical predictions to within 3 parts per million. This result combined with some theoretical assumptions was used to exclude a Higgs lighter than a few MeV [11].

- **Higgs bremsstrahlung:**
  The theoretical basis of this limit is just the electroweak model and hence relatively free of theoretical uncertainties. The experiment looked for a Higgs Boson produced through a bremsstrahlung process in an electron beam-dump set-up. No signal was observed. As a result, the region
  \[ 1.2 \text{MeV}/c^2 < m_{H^0} < 50 \text{MeV}/c^2 \]
  was excluded [12].

- **Pion decay, \( \pi \to e\nu H^0 \):**
  The SINDRUM Collaboration looked for rare pion decays compatible with Higgs Boson production [13]. The negative results allowed them to exclude the region
  \[ 10 \text{MeV}/c^2 < m_{H^0} < 110 \text{MeV}/c^2 \]
  The same channel was used in a completely different approach by reanalyzing data from a beam-dump experiment [14]. The excluded mass region is somehow smaller but in some areas the exclusion is much stronger.

- **Kaon decay, \( K \to \pi H^0 \):**
  A search for a Higgs signal in this channel was performed by the two experimental collaborations NA31 at CERN [15] and E731 at Fermilab [16]. The theoretical calculations used at that time to deduce the limit contained large uncertainties. However the branching ratios have since been recalculated with much smaller uncertainties, yielding similar numbers [17]. The final conclusion was that a Higgs Boson in the mass region
  \[ 100 \text{MeV} < m_{H^0} < 2m_\mu \]
  was very unlikely.

- **\( \eta \) and \( \eta' \) decays:**
  An experiment carried out at Serpukhov [18] looked for a Higgs Boson produced in \( \eta \) decays and disintegrating into two muons. Using
the theoretical calculations available at that time they excluded a Higgs Boson in the mass region

\[ 2m_\mu < m_{H^0} < 400 \text{ MeV/c}^2 \]

At a later date, however, the theory turned out to be incorrect but unfortunately the analysis was not updated. There is also a second analysis concerning \( \eta \) particles in which the channel \( \eta' \to \eta H^0 \) was used [19] to exclude the region

\[ 10 \text{ MeV/c}^2 < m_{H^0} < 210 \text{ MeV/c}^2 \]

- \( \Upsilon \) decays:
  A higher mass region was covered by searches for the decay

\[ \Upsilon \to H^0 \gamma \]

by the CSUB Collaboration [20]. Unfortunately large theoretical uncertainties existed due to QCD high order corrections and to relativistic effects. Assuming the calculations were correct a Higgs Boson with a mass lighter than 5 GeV/c\(^2\) was excluded.

This is a brief summary of Higgs Boson searches before LEP provided data. Most of the limits were suspect due to hadronic effects present in the Higgs Boson production and decay mechanisms.

5 Higgs Boson Production at LEP 100

There are two main mechanisms by which a Higgs Boson is produced in \( e^+e^- \) collisions at LEP 100. The first is a bremsstrahlung process where the \( Z^0 \) Boson radiates a Higgs Boson and then decays into a fermion pair (Figure 5a). This process was suggested by Bjorken [21].

The second mechanism is a higher order process. The Higgs Boson is produced via the coupling of the \( Z^0 \) to a triangle of fermions or W's, decaying into a Higgs Boson in association with a photon. The corresponding diagram is shown in Figure 5b. Since this reaction is a perturbative process, its cross section is at least an order of magnitude smaller than that of the Bjorken process in the search region relevant at LEP 100 \((m_{H^0} < 60 \text{ GeV/c}^2\)). In addition it suffers from a severe background of final state radiative hadronic processes, resulting in a very poor signal to noise ratio [22]. This leaves the Bjorken process as the best reaction to search for a Higgs Boson at LEP 100.

In the following the topology and kinematics of the Bjorken process are
Figure 6: The cross section for Higgs Boson production (via the Bjorken process) as a function of the Higgs mass at LEP 100 explored in more detail. The reaction is given by

\[ e^+e^- \rightarrow Z^0 \rightarrow H^0Z^0 \rightarrow H^0f\bar{f}. \]  

The corresponding cross section is obtained by calculating the tree level Born diagram [23]. This is then dressed with the Improved Born Approximation (IBA) [24] together with a correction arising from a top quark triangle graph at the ZZH vertex [25]. The IBA cross section is then convoluted with an exponentiation function [26] in order to incorporate the effects of Initial State photon Radiation (ISR). The resulting cross section as a function of the Higgs Boson mass is shown in Figure 6. It is to be noted that the dependence on the top mass is greatly reduced due to the vertex correction. This can be seen in Figure 7, where the cross section for \( m_{H^0} = 50 \text{ GeV}/c^2 \) is depicted with (dashed) and without (solid) the top triangle vertex corrections.

The key to the topological and kinematical signature of the Bjorken process is the boosts of the Higgs Boson and the virtual \( Z^0 \) recoiling against each other.

Using the differential cross section \( d\sigma(Z^0 \rightarrow H^0Z^{0*})/dp_{H^0} \), where \( p_{H^0} \) is the momentum of the recoiling Higgs Boson, it is possible to calculate the average of any momentum dependent
quantity \( \langle f(p_{H^0}) \rangle \) via

\[
\langle f(p_{H^0}) \rangle = \frac{\int f(p_{H^0}) \frac{d\sigma}{dp_{H^0}}}{\int (d\sigma/dp_{H^0})}
\] (5)

This formula can be used to calculate the average Higgs Boson momentum as a function of the Higgs Boson mass \([27]\). The result is shown in Figure 8. The interesting feature of this plot is the relatively high average momentum, \( \langle p_{H^0} \rangle \approx 8.3 \text{ GeV}/c \), for low masses.

This means that the \( Z^0^* \) recoiling against the Higgs Boson will have an observable boost even when the \( H^0 \) is very light. This feature is discussed in more detail in section 6.1.

A Higgs Boson at rest decays into a back-to-back fermion pair. However, due to its boost, the fermion pair has an opening angle \( \varphi \) dependent on the boost direction. For simplicity \( \varphi \) is calculated when the Higgs is boosted in the direction perpendicular to both fermions. This is given by

\[
\varphi = 2 \tan^{-1} \left( \frac{\beta_f}{\gamma \beta} \right)
\] (6)

where \( \gamma \beta \) is the Higgs Boson boost and \( \beta_f \) is the fermion velocity in the Higgs rest frame. Using equation (5) it is possible to calculate the average opening angle \( \langle \varphi \rangle \). The result is depicted in Figure 9 (solid line). It should be noted that at the thresholds (e.g. \( b\bar{b} \)), the fermions are produced at rest and therefore are boosted along with the Higgs, yielding a zero opening angle.

An immediate conclusion from this plot is that if the Higgs has a mass below about 15 GeV/c\(^2\), the average open-
ing angle $\varphi$ is below $70^\circ$. Therefore the topology tends to be that of a mono-jet recoiling against the $Z^0$ decay products, while jets originating from a heavier Higgs Boson tend to open but are still not back-to-back.

In a similar way the average opening angle $\varphi$ of a pair of leptons originating from the $Z^0$ decay is calculated (Figure 9 dashed line). Note that the heavier the Higgs Boson, the lighter the virtual $Z^0$ mass, resulting in a higher boost and smaller $\varphi$.

The various Higgs Boson decay modes have already been discussed in section 2. The $Z^0$, recoiling against the Higgs Boson, decays into hadrons ($\sim 70\%$), charged leptons ($\sim 10\%$) and neutrinos ($\sim 20\%$), similarly to a real $Z^0$.

The various decay modes of both the Higgs Boson and the $Z^0$ determine the search channel, while the complementary nature of the boosts of the Higgs and the virtual $Z^0$ determines the specific experimental signature within a given channel. Both the decay modes and the boosts are clearly dependent on the Higgs Boson mass. As a result different search strategies have been developed in different mass regions.

6 Higgs Searches

In this section an overview of the SM Higgs searches performed by ALEPH [28, 29, 30, 31, 32, 33], DELPHI [34, 35, 36, 37], L3 [38, 39, 40, 41] and OPAL [42, 43, 44, 45, 46, 47] is presented.

6.1 Long Lived Higgs Boson ($m_{H^0} < 2m_\mu$)

A very light Higgs Boson decays mostly to a pair of electrons or photons. Its proper life time (for $m_{H^0} > 2m_\mu$) is given by

$$\tau (\text{cm}) \approx 0.120/m_{H^0}(\text{GeV}/c^2)$$ (7)

As already shown (Figure 8) the average momentum of a very light Higgs Boson is roughly $8.3 \text{ GeV}/c$. Its mean boost is therefore given by

$$\gamma = \beta c = \sqrt{\frac{m_{H^0}}{m_{H^0}}(\text{GeV}/c)} \approx \frac{8.3(\text{GeV}/c)}{m_{H^0}(\text{GeV}/c^2)}$$ (8)

The combination of the two previous quantities determine the average decaying distance

$$l (\text{cm}) = \gamma \beta c \tau \approx \frac{1}{m_{H^0}(\text{GeV}/c^4)}$$ (9)

and plotted in Figure 10.

The step at the $\mu\mu$ threshold of almost six orders of magnitude clearly defines experimentally the search strategy for a very light Higgs Boson. Above the di-muon threshold the Higgs Boson decays at its creation point. However, below this threshold, the Higgs Boson might travel meters before its decay and therefore escape the apparatus without being detected. On the other hand the $Z^0$ recoiling against the Higgs Boson will have an average momentum of $8.3 \text{ GeV}/c$. A simple calculation shows

\footnote{Like a Weakly Interacting Neutral Particle, it would not be seen in any of the detectors of the experiment.}
that if each of the fermions, it decays to, carries 4.15 GeV/c they will not be exactly back-to-back but will have an acollinearity \( \phi \approx \pi - 2 \cdot \frac{4.15}{4\pi} \approx 170^\circ \). Therefore the signature of a very light Higgs Boson will be an acollinear fermion pair recoiling against an unseen Higgs Boson or against detached vertices (when the Higgs Boson becomes heavier and decays inside the detector).

6.1.1 Invisible Higgs

If the \( H^0 \) is not detected, an acoplanar pair of muons or electrons coming from the \( Z^0 \) decay remains. The high acoplanarity of the expected signal (Figure 11) is the most characteristic signature of such events. The main source of background comes from radiative \( Z^0 \) leptonic events in which the photon escapes detection:

\[
e^+e^- \rightarrow Z^0 \rightarrow l^+l^- (\gamma)
\]

In addition, \( \tau \)-pairs with only two charged particles in the final state,

\[
e^+e^- \rightarrow \tau^+\tau^- \rightarrow \text{two prongs}
\]

may also be background.

The four LEP collaborations have performed searches for this kind of very light Higgs Boson. Details of the analyses can be found in references [30, 35, 39, 44]. The main requirements can be summarized as follows:

- Two energetic tracks are demanded to reduce the \( \tau \)-pair background. In addition both tracks should have a certain acoplanarity or acollinearity in order to reject background from di-electrons or di-muon events.
Figure 12: Number of expected signal events in the invisible Higgs Boson analysis (triangles) and in the search for a $H^0$ decaying inside the detector (squares) as a function of the Higgs Boson mass by the DELPHI Collaboration.

- The level of calorimetric activity unassociated to charged tracks must be below some threshold. This requirement is intended to reject the $Z^0 \rightarrow e^+e^-\gamma$ background.

- Any detected activity should be far away from the beam axis in order to get rid of beam related noise.

None of the LEP Collaborations found any candidate in this channel. As an example, Figure 12 (triangles) shows the number of expected Higgs Boson events expected in the analysis performed by the DELPHI Collaboration.

### 6.1.2 Higgs Boson decaying in the detector

If the Higgs Boson mass is larger than a few tens of MeV/$c^2$, the average decay length is of the order of 1 meter, as shown in Figure 10. Therefore such a Higgs Boson will decay predominantly inside the detector.

The first searches in this mass region, performed by ALEPH [28] and DELPHI [35], looked for the Higgs Boson products directly. They made use of the fact that $H^0$ decays predominantly into $e^+e^-$ pairs after flying a macroscopic distance. Isolated pairs of oppositely charged particles pointing at a common point far away from the main vertex were looked for. This particular topology allowed searches for the Higgs Boson produced via:

$$e^+e^- \rightarrow H^0Z^0, \quad H^0 \rightarrow e^+e^-$$

$$Z^0 \rightarrow q\bar{q}, l\bar{l}, \nu\bar{\nu}$$

Since so many possibilities were considered the analyses were rather complex. L3 [39], OPAL [44] and a new ALEPH analysis [32] used a different approach based on a larger amount of data. They concentrated their efforts in the cleaner leptonic channels, although the branching ratios are smaller. The main Higgs Boson production modes used were

$$Z^0 \rightarrow \nu\bar{\nu}H^0$$

and

$$Z^0 \rightarrow l^+l^-H^0.$$
Figure 13: Light Higgs Boson candidate produced through the reaction $e^+e^- \rightarrow H^0\mu^+\mu^-$, $H^0 \rightarrow \mu^+\mu^-$ found by the L3 Collaboration. The four detected particles are muons.

the beam-pipe. These events are generally rejected by requiring a minimum transverse momentum with respect to the beam-axis.

An important source of background for $Z^0 \rightarrow lH^0$ are $Z^0$ leptonic decays with a radiated photon converted in the detector. Another background occurs when there is a virtual gamma decaying into a pair of fermions instead of a real photon. Such events will be discussed in detail in section 6.3.1.

Figure 13 shows a light Higgs candidate produced through the channel

$$e^+e^- \rightarrow H^0Z^{0*}, \quad H^0 \rightarrow \mu^+\mu^-$$

found by the L3 Collaboration. The muon-pair with a small opening angle would correspond to the Higgs Boson decay products. The high energy lepton-pair would come from the virtual $Z^{0*}$ decay.

Some candidates were found by several experiments. However they are compatible with the estimated background and fewer than the expected SM Higgs Boson signal. The number of Higgs events expected in the DELPHI Collaboration from this kind of analysis as a function of $m_{H^0}$ is shown in figure 12 (squares). It is to be noted that the combination of both analyses excludes a Higgs Boson in the mass range $0 < m_{H^0} < 2m_{\mu}$. All LEP experiments obtained similar results with more than 95% CL.

6.2 The Ambiguous Region ($2m_{\mu} < m_{H^0} < 2m_{\tau}$)

When the Higgs Boson is heavier than $2m_{\mu}$ its lifetime is no longer observable. It decays promptly at the interaction point. However, as already discussed in section 2, its decay modes in the mass region $2m_{\mu} < m_{H^0} < 2m_{\tau}$ are ambiguous.

ALEPH [28] and DELPHI [34] performed the pioneering LEP work in this area with the first data taken in 1989. They took advantage of the fact that the Higgs Boson decays mainly into two charged prongs. ALEPH looked for all $Z^{0*}$ decays

$$e^+e^- \rightarrow H^0Z^{0*}, \quad H^0 \rightarrow 2\text{ prongs}$$

$$Z^{0*} \rightarrow l\bar{l}, q\bar{q}, \nu\bar{\nu}$$

while DELPHI concentrated its effort on the hadronic channel, $Z^{0*} \rightarrow q\bar{q}$. The search consisted in looking for isolated and narrow jets coming from the
Higgs Boson decay. The model dependent branching ratios [7, 9] were used to calculate the Higgs Boson detection efficiency. DELPHI stressed that their analysis was very weakly model dependent, since the case with lowest efficiency was considered to extract the final Higgs limits. Both Collaborations excluded a Higgs Boson in the region

\[ 2m_{\mu} < m_{H^0} < 1 \text{ GeV}/c^2 \]

The L3 study [39] and a new ALEPH analysis [32] were mainly based on the production mode

\[ Z^0 \rightarrow l^+l^- H^0, H^0 \rightarrow \text{anything}. \]

L3 Higgs Boson detection efficiencies were found to be quite independent of the Higgs Boson decay mode. Considering all reasonable Higgs Boson decays in that region, L3 excluded this mass range. ALEPH used fixed branching ratios and therefore its analysis was model dependent. However given the very high number of expected events, more than a hundred, with no candidates found, their results can be considered model independent for all practical purposes.

Finally OPAL [46] performed perhaps the most model independent study. To avoid any assumption on the Higgs Boson decay modes they used the complementary channels:

\[ Z^0 \rightarrow e^+e^-, \mu^+\mu^- \]
\[ H^0 \rightarrow \text{non-electromagnetic} \]

and

\[ Z^0 \rightarrow \nu\bar{\nu} \]
\[ H^0 \rightarrow \text{electromagnetic} \]

Even though every possible Higgs decay would have passed the selection criteria, some weak assumptions were needed when calculating the detection efficiency and obtaining the actual limits. They reanalyzed the long-lived Higgs Boson mass region \( m_{H^0} < 2m_{\mu} \). Figure 14 depicts the excluded \( H^0 \) production branching ratio, relative to the Standard Model, versus the Higgs Boson mass. They excluded a SM Higgs Boson up to 11 GeV/c^2.

6.3 Intermediate Region \( (m_{H^0} > 2m_{\tau}) \)

The intermediate region extends from the \( H^0 \rightarrow \pi\pi \) production threshold to well above the \( H^0 \rightarrow b\bar{b} \) threshold \( (m_{H^0} \approx 40 - 60 \text{ GeV}/c^2) \). Being the current Higgs Boson search front, this review emphasizes the latter region.

The production channels for a Higgs Boson above the \( b\bar{b} \) threshold and their relative rates are given in Table 2.
As can be seen, the most abundant channel is when both the Higgs Boson and the virtual \( Z^{0*} \) decay hadronically. These events produce four jets with a high portion coming from heavy quarks, since the Higgs Boson tends to decay into \( b\bar{b} \) as soon as this channel is kinematically possible. (See section 2). Unfortunately this channel suffers from a very severe background coming from normal \( q\bar{q} \) events. At LEP 100 the QCD rate is 4-5 orders of magnitude higher than the Higgs Boson production rate. As a result this channel has not yet been used by any of the LEP experiments for the SM \( H^0 \). The second most abundant channel corresponds to

\[
e^+e^- \rightarrow H^0 Z^{0*}, Z^{0*} \rightarrow e^+e^-, \mu^+\mu^-
\]

This is the main production mode used by all four collaborations in search of the Higgs Boson. The Charged Leptonic channels

\[
e^+e^- \rightarrow H^0 Z^{0*}, Z^{0*} \rightarrow e^+e^-, \mu^+\mu^- 
\]

have a very clear and distinct signature, but their combined branching ratio is only 1/3 of the Neutrino channel. As indicated in Table 2, the rate of final states with hadrons and a \( \tau \)-pair is relatively large. Unfortunately \( \tau \) particles are difficult to identify in a hadronic environment, therefore their detection efficiency is low, typically around 15%. Finally there are several final states with four leptons, but even if some experiments have looked for a Higgs Boson in those channels, their contribution to the total number of expected events is negligible.

Therefore, below, a description of only the searches in the Charged Leptonic and Neutrino channels is given. Both have clear signatures and reasonable efficiencies.

### 6.3.1 Charged Leptonic Channel

These events constitute the clearest signal for Higgs Boson searching at LEP 100. They are characterized by two energetic and isolated leptons, coming from the \( Z^{0*} \) decay, and by some hadronic activity from the Higgs decay. As explained in section 5, the topology changes with the Higgs mass. When the Higgs Boson mass is below about 15 GeV/\( c^2 \), it tends to manifest itself as a mono-jet recoiling against a lepton pair which carries most of the event energy. At high masses the energy distri-

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<th>Channel</th>
<th>Rate (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q\bar{q} \rightarrow \nu\bar{\nu} )</td>
<td>18.9</td>
<td>clear signature, reasonable efficiency</td>
</tr>
<tr>
<td>( \tau^+\tau^- )</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>( q\bar{q} \rightarrow e^+e^- )</td>
<td>3.2</td>
<td>low selection efficiency</td>
</tr>
<tr>
<td>( \tau^+\tau^- )</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>( q\bar{q} \rightarrow \mu^+\mu^- )</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>( \tau^+\tau^- )</td>
<td>4.2</td>
<td>low selection efficiency</td>
</tr>
</tbody>
</table>

Table 2: The relative rates of the different channels in the Bjorken process, \( Z^0 \rightarrow H^0 Z^{0*} \rightarrow f^+\bar{f}^+ f\bar{f} \).
bution is swapped: most of the center-of-mass energy is materialized into two hadronic jets with a large opening angle, while the lepton pair is closed with a lower invariant mass.

The main selections for this kind of signal can be summarized as follows [32, 36, 41, 47]:

**Lepton identification** Two energetic tracks are required to be identified as electrons or muons. Some analyses consider two identification levels and only one track should fulfill the most stringent criteria.

**Topology** The two leptons are required to have a large opening angle and to be well isolated from the rest of the event. These requirements are intended to reject the background from $e^+e^- \rightarrow b\bar{b}$, with the $b$ quarks decaying semi-leptonically.

DELPHI found the first Higgs boson candidate in the electron channel in the data collected in 1990. Figure 15 shows the event, where two nicely isolated electrons can be observed. The mass recoiling against the lepton pair, corresponding to the Higgs candidate mass, is $35 \pm 5$ GeV/$c^2$. The mass calculated from the observed hadronic activity is somehow smaller ($17$ GeV/$c^2$), but there are indications of missing energy in the forward direction.

L3 has reported on two other candidates collected in the 1991 run. Figure 16 shows the L3 candidate in the muon channel, with high mass, $70.4 \pm 0.7$ GeV/$c^2$. This event is particularly

![Figure 15: DELPHI Higgs Boson candidate in the electron channel: $e^+e^- \rightarrow H^0e^+e^-$, $H^0 \rightarrow q\bar{q}$.

![Figure 16: L3 candidate in the muon channel: $e^+e^- \rightarrow H^0\mu^+\mu^-$, $H^0 \rightarrow q\bar{q}$.

The two long tracks on the left upper part of the picture would correspond to the two muons from the virtual $Z^0$ decay. The third long track (coming from the interactions point) on the right side of the picture is also identified as a muon.
Figure 17: L3 candidate in the electron channel. The two tracks associated with long boxes, corresponding to electromagnetic energy, would be the electrons from $Z^0 \rightarrow e^+ e^-$. The hadronic activity would be the Higgs decay products.

interesting since, as can be observed in the picture, there is a third muon belonging to one of the jets. This seems to indicate that the hadronic activity in the event comes from a pair of heavy quarks with one of them decaying semi-leptonically. This would favor a Higgs interpretation of the event, since at this mass the $H^0$ tends to decay into $b\bar{b}$. Note also the small opening angle of the di-muon which recoils against two jets which are almost back-to-back. This topology is also typical for a Higgs Boson as explained in section 5.

Figure 17 shows the L3 candidate event in the electronic channel. The mass recoiling against the di-electron is compatible with a $31.4 \text{ GeV}/c^2$ mass

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Chan.</th>
<th>Mass(*) (GeV)</th>
<th>Expected Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEL-PHI</td>
<td>$e^+e^-q\bar{q}$</td>
<td>$35.0 \pm 5.0$</td>
<td>$0.33 \pm 0.05$</td>
</tr>
<tr>
<td>L3</td>
<td>$e^+e^-q\bar{q}$</td>
<td>$31.4 \pm 1.5$</td>
<td>$1.6 \pm 0.3$</td>
</tr>
<tr>
<td>L3</td>
<td>$\mu^+\mu^-q\bar{q}$</td>
<td>$70.4 \pm 0.7$</td>
<td>$1.7 \pm 0.2$</td>
</tr>
</tbody>
</table>

(*)Calculated as recoil mass of the di-lepton system.

Table 3: Higgs candidates seen by the different experiments

Higgs Boson. Note the large opening angle of the di-electron emerging from the $Z^0$, compatible with that expected from a Higgs Boson event.

This nice harvest of Higgs candidates collected by the LEP experiments, summarized in Table 3, seems to have an explanation in a physical background which is difficult to eliminate: four fermion events. The main graphs contributing to this type of events are depicted in Figure 18.

The cross section for these reactions is small as they are a result of higher order diagrams. Nevertheless it is large enough to be the dominant background in the Charged Leptonic channel. The number of noise 4-fermion events expected in the LEP experiments where candidates were observed is shown in Table 3. This number is consistent with the candidates observed.

The properties of $e^+e^- \rightarrow e^+e^-q\bar{q}$ events generated with a Monte Carlo program were studied in order to understand better this important background. Figure 19a shows the mass recoiling against the lepton pair at the
Figure 18: Diagrams contributing to the cross section of 4-fermion events: $e^+e^- \rightarrow l^+l^- q\bar{q}$.

generation level, without any detector simulation, for light (u,d,s) and heavy (c,b) quarks [48]. No large differences are expected if muons rather than electrons are considered in the final state.

As can be observed the empty histogram is peaked at low(high) masses, when the quark(lepton) pair comes from a quasi-real radiated photon. Therefore naively the 4-fermion background should not be expected in the Higgs mass region of 30-70 GeV/c$^2$, where the candidates seem to be. However the cuts used to remove the background might distort and bias the original mass distribution. In order to understand the effect of these cuts, requirements similar to those applied by the experiments were demanded:

- A minimum number of charged particles (> 5)

![Diagram](image)

Figure 19: Mass recoiling against the di-electron system for 4-fermion events $e^+e^- \rightarrow e^+e^- q\bar{q}$ for light (u,d,s) and heavy (c,b) quarks. Before (a) and after (b) typical cuts applied for Higgs Boson selection in the Charged Leptonic channel.
• $E_1^e + E_2^e > 12$ GeV and $\text{Min}(E_1^e, E_2^e) > 2$ GeV, where $E_1^e, E_2^e$ stand for the energy of the first and second electron respectively.

• An opening angle between the two leptons larger than $20^\circ$.

• Isolation angle for the electrons larger than $20^\circ$.

Figure 19b shows the recoiling mass spectrum of the surviving background events for light and heavy quarks. The resulting distributions have a low mass peak around 10 GeV/$c^2$. However this region is not relevant for the present searches as they are focused on the high mass region. A second peak, especially prominent for the heavy quarks, is present in the recoiling mass distributions at around 75 GeV/$c^2$. It can be concluded that the $b$ and $c$ quarks tend to concentrate on masses larger than 60 GeV/$c^2$. Therefore the heavy (70.4 ± 0.7 GeV/$c^2$) L3 candidate, with the hadronic activity probably coming from heavy quarks, seems also to be fully compatible with the 4-fermion hypothesis.

6.3.2 Neutrino Channel

The $Z^0$ branching ratio into a Higgs Boson and a pair of neutrinos is roughly three times greater than the Charged Leptonic channel presented in the previous section (See Table 2). As discussed in section 5, these events are characterized by a very clear signature. If the Higgs mass is below about 15 GeV/$c^2$, the topology tends to be that of a mono-jet recoiling against unobserved neutrinos which carry a large amount of missing energy and missing transverse momentum. An example of a 15 GeV/$c^2$ Higgs Boson Monte Carlo simulated event is given in Figure 20a. Jets originating from a heavier Higgs Boson tend to open in angle but are still not back-to-back, as can be seen in Figure 20b, where a simulated 40 GeV/$c^2$ Higgs event is shown. In this case the missing energy carried away by the neutrinos is reduced making it harder to detect a heavier Higgs even before the falling production cross section is taken into account. Although the signal is very clear there is a large number of background sources. In fact, before LEP started to run, it was believed to be very difficult, if not impossible, to use this channel to search for the Higgs [4]. Fortunately all LEP experiments have performed better than expected in this area.

Some of the low mass backgrounds show mainly in the phase-space region close to the beam pipe. Beam interactions with gas in the beam-pipe produce events with a large amount of missing energy. However the missing momentum points down the beam pipe. The same predominantly forward activity is characteristic of photon-photon interactions, where a gamma emitted by an electron collides with a gamma emitted by a positron. In these reactions the momentum transfer is peaked at zero and the scattered $e^+e^-$ tend to go down the beam-pipe undetected. The products of the gamma-gamma collision may fake a low mass Higgs. However most of this background can be rejected by re-
Figure 20: Example of Higgs production in association with a virtual $Z^0$ decaying into a pair of neutrinos for (a) $m_{H^0} = 15$ GeV and (b) $m_{H^0} = 40$ GeV. The trajectories of charged(neutral) particles are represented by curves(dashed lines).

Figure 21: Example of a very forward event detected by the DELPHI Experiment.

requiring the transverse momentum with respect to the beam to be larger than a few GeV/c. Figure 21 shows an example of this kind of background, a very forward event detected by the DELPHI Experiment. As can be observed, the missing momentum, indicated by the thick arrow, points near the beam direction. A relatively low activity in the detectors at low polar angles, or a large angle ($>10-30^\circ$) between the total missing momentum and the beam, are typical requirements to avoid this background.

Hadronic events are a serious source of background where the initial quark energies are mis-measured. This loss of energy may be due to unavoidable physical process, like the semileptonic decay of heavy quarks, with neutrino production, or other detector dependent phenomena. As an illustration Figure 22
Figure 22: Energy carried away by neutrinos produced in hadronic $Z^0$ decays at LEP 100 (the distribution is normalized to 1).

shows the probability for the energy carried away by neutrinos in $q\bar{q}$ events. As can be seen there is a very long tail up to 50 GeV at the $10^{-4}$ probability level. When the search must filter of the order of $10^5$ events, as it is the case at LEP 100, such a background might pose a serious problem. A very similar tail can be obtained by detector effects, like a non hermetic detector (cracks or beam pipe) or calorimeter response fluctuations. Even if the energy of a given jet is not well measured, in most cases the direction of the original parton is well defined. For this reason many of the requirements demanded in the Neutrino channel are based on topological variables rather than on energy measurements. Some requirements of the different analyses are described below. It is not the aim of this review to present in detail all cuts used to reject the abundant background, but rather to give a general view of the requirements demanded.

Common variables in the Neutrino analyses used by the four LEP Collaborations are the acollinearity and the acoplanarity. In order to define them the event is divided into two hemispheres, usually using the plane perpendicular to the thrust axis. Then a jet is built with all particles in each hemisphere. The acollinearity (acoplanarity) is then usually defined as the
complement of the angle between the two jets (when projected onto the plane perpendicular to the beam axis). Background hadronic events tend to yield two back-to-back jets, corresponding to acollinearity and acoplanarity close to zero, even if a large amount of energy is missing. This is not the case for genuine Higgs events as illustrated in Figure 23, where data and 50 GeV/c² Higgs signal acollinearity distributions are shown by the OPAL Collaboration after other selection cuts.

Hadronic events with an energetic radiated photon might fake Higgs Boson events if the photon is missed by the detector. Figure 24 shows an example of such an event detected by the ALEPH Collaboration, where the photon is well detected. Had the photon escaped detection this event would have been a perfect Higgs candidate. These potential candidates and other kinds of background are rejected by a variable also widely used in missing energy searches: the energy contained in a cone around the missing momentum. Figure 25 depicts such a variable used in the DELPHI analysis for a 50° half angle cone. It is to be noted the agreement found between Monte Carlo for the background processes, coming mainly from hadronic events, and the data.

The most severe background events are those incorporating several effects together: initial or final state radiation, energy carried away by neutrinos, calorimetry fluctuations, detector cracks, multijet structure, etc. Hitherto even those very difficult events have been rejected using topological variables. One of those variables, S, is obtained by forcing the event into three jets and adding the three possible angles between the jets. Figure 26 shows the distribution of S for signal and back-
The background events tend to peak at 360°, since they lie on a plane, while the Higgs events show a rather flat distribution.

The selection requirements discussed above are merely intended to give an idea about Higgs searching techniques in this difficult channel. In general LEP collaborations have performed several analyses, each of them tuned to a given mass region or to a given type of topology. At present no relevant candidate in the Neutrino channel has been reported by any of the experiments.

7 Mass Limits

After reviewing the analyses of the different channels, a comparative study of the results obtained by the four LEP experiments so far is presented. This section concentrates on the heavier Higgs Boson region. [33, 37, 41, 47].

7.1 Individual Experiment Results

The cuts used in the recent analyses have been tuned to give the highest possible signal to noise ratio while retaining a high efficiency for a 50-55 GeV/c² Higgs Bosons. These efficiencies, in the various channels, are given in Table 4 for \( m_{H^0} = 50 \) GeV/c².

It is interesting to consider a global Higgs detection efficiency, \( \epsilon_g \), in order to get a better idea of the efficiencies achieved by the different experiments. \( \epsilon_g \) is defined to be the sum of the efficiencies in the different channels weighted by the corresponding branching ratios, i.e.

\[
\epsilon_g = \sum_{f=\mu, e, \nu} \epsilon_{Hf} \frac{BR(Z \rightarrow Hf\bar{f})}{\sum_{f'} BR(Z \rightarrow Hf')}
\]

The global efficiencies as a function of the Higgs Boson mass are shown in Figure 27. As can be noted around...
\( m_{H^0} = 50 \text{ GeV}/c^2 \) the efficiencies range between about 44% (DELPHI) and 62% (ALEPH).

In deriving a limit the number of expected events is reduced by the possible systematic errors. The different systematic error sources in the dominant neutrino channel for the different experiments are compared in Table 5.

Note that ALEPH add 2% linearly in order to allow unexpected background. The rest of the errors are added in quadrature.

The general procedure of deriving a limit was explained in section 3. Here it is demonstrated in the presence of candidate events with known mass. Figure 27 (based on L3 results [41]) shows the number of expected Higgs Boson events in the various channels as a function of the Higgs mass.

![Figure 27: The global efficiency for Higgs detection as a function of the Higgs Boson mass.](image)

<table>
<thead>
<tr>
<th>Source</th>
<th>ALEPH</th>
<th>DELPH</th>
<th>L3</th>
<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production ( \sigma )</td>
<td>1.0</td>
<td>2.0</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Higgs BR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity, Normalization</td>
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<td>0.6</td>
<td>0.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Fragmentation</td>
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<td>2.0</td>
<td>1.5</td>
<td>3.2</td>
</tr>
<tr>
<td>Detector Sim.</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monte Carlo Statistics</td>
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<td>1.5</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Unforeseen Background</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5: The systematic errors (%) reported by the different experiments in the Neutrino channel.

As commented in section 6.3, the contribution of the \( \tau^+\tau^- q\bar{q} \) channel (dashed dot line) is an order of magnitude less than that of the other Charged Leptonic channels (dotted line) due to low selection efficiency. This contribution is practically negligible. The number of expected events in the Neutrino channel is given by the dashed line and the total number by the solid line. In order to derive a limit the \( e^+e^- q\bar{q} \) event observed by L3 is considered to be compatible with a Higgs Boson with \( m_{H^0} = 31.4 \pm 1.5 \text{ GeV}/c^2 \). Naively, this event could be taken as a Higgs candidate and a limit could be derived based on \( N_{exp}(m_{H^0}) > 4.7 \) expected events. However, this candidate can be assigned
to a specific mass window, in this case rather narrow due to the excellent resolution of the L3 detector. Thus a Gaussian with a \( \sigma = 1.5 \) GeV/c\(^2\) and amplitude 1.0 is plotted. A window of \( \pm 2\sigma \) around its mean value is opened and a limit is derived based on one observed event within that window, and zero events outside. That corresponds to 4.7 and 3.0 expected Higgs events accordingly. Drawing the corresponding line (broken straight line), it can be seen that up to 52.0 GeV/c\(^2\) the total number of expected events is above the number needed to set a limit at the 95\% confidence level. L3 therefore excludes a Higgs Boson up to 52.0 GeV/c\(^2\).

The drawback of the above procedure used to derive the limit in the presence of a candidate lies in its discontinuity at the \( \pm 2\sigma \) window edges. It is obvious that there is a finite probability for an event observed at \( m_{H^0} \) to originate from a Higgs Boson with a mass \( m_{H^0} \) which is more than \( 2\sigma \) deviations away. This probability can be estimated by

\[
P = 2(1 - f_{req}(\sqrt{\chi^2})) = \text{prob}(\chi^2, 1)
\]

where

\[
f_{req}(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} \exp(-u^2/2) du.
\]

and

\[
\chi^2 = (m_{H^0} - m_{H^0})^2 / \sigma^2
\]

However, there is not a well defined prescription of how to use the above probability or similar ones in order to derive the 95\% CL limit. A few rigorous prescriptions exist in the literature [41, 49]. They all give similar results but they all become rather complicated when there are more than two candidate events and when expected background is taken into account. For the purposes of this review a simpler, somewhat naive method will be shown [50]. Here the probability \( P \) is interpreted as the fraction of the event that is observed at \( m_{H^0} \). This fraction is 1 when \( m_{H^0} = m_{H^0} \) and is approaching 0 as \( m_{H^0} \) gets far away from \( m_{H^0} \). When there are many candidate events their probabilities are simply added in order to estimate their contribution at any mass \( m_{H^0} \). Once the total number of observed events is known at \( m_{H^0} \) the usual Poisson distribution is used to derive the 95\% CL. However, the Poisson distribution is not well defined when the
Figure 29: The number of Higgs Boson events expected in order to exclude a Higgs at the 95% confidence level, when $N_{\text{observed}}$ events are conservatively taken as candidates.

The number of observed events is a fraction, e.g. 1.3 etc. This can be obtained by a simple interpolation. In Figure 29 (based on table 1) the number of expected events needed to be seen in order to set a 95% CL limit as a function of the number of observed candidate events is shown. Conservatively all candidate events are considered as signal events.

The linear shape of this plot suggests that the Poisson limit for any number of observed candidate events can be obtained by a simple linear interpolation from its two neighbouring points. For example, if we observe 0.7 events at some mass $m_H$, 4.26 events should be expected in order to set a 95% CL on the Higgs mass. The resulting 95% CL curve of this procedure is shown in Figure 28 (dashed line). More rigorous approaches [41, 49] give similar results. The extension of this procedure to any number of observed candidate events is straightforward, and will be used in the next section.

After applying similar procedures all experiments obtained 95% CL lower limits on the Higgs Boson mass.

The results are summarized in Table 6. The number of hadronic decays used to derive the limits is also given. This number is closely related to the luminosity, and is given for comparison purposes.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$N_{\text{hadrons}}$</th>
<th>Higgs Lower Limit (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>488,000</td>
<td>53.0</td>
</tr>
<tr>
<td>DELPHI</td>
<td>330,000</td>
<td>47.0</td>
</tr>
<tr>
<td>L3</td>
<td>408,000</td>
<td>52.0</td>
</tr>
<tr>
<td>OPAL</td>
<td>494,000</td>
<td>52.6</td>
</tr>
</tbody>
</table>

Table 6: The lower limit on the Higgs Boson mass obtained by the different experiments, and the corresponding number of hadronic decays used.

7.2 A Combined Higgs Limit

Here the liberty is taken of deriving a limit based on the combined results of all LEP experiments. First the number of expected events as a function of the Higgs mass is combined. The result is shown in Figure 30.

The obtained total number of expected events is now used in order to de-