Measurement of Z boson pair production and a search for the Higgs boson in e+e-collisions at LEP
van Vulpen, I.B.

Citation for published version (APA):
van Vulpen, I. B. (2002). Measurement of Z boson pair production and a search for the Higgs boson in e+e-collisions at LEP
Chapter 7

Higgs production (SM Higgs decay)

In this chapter a search for the SM Higgs boson is presented in case both the Higgs and the Z boson decay into a quark anti-quark pair. The analysis is an extended version of the event-by-event probability computation as introduced in section 5.4 and the chapter starts with a discussion of these various extensions and their implications on the probability computation. In section 7.2 two techniques used to extract mass information from the event are discussed in detail. This is done to illustrate the advantage of using the SM prediction for the Higgs boson’s (changing) properties as a function of its mass.

The Higgs probability distributions and their characteristics are presented in section 7.3, while in section 7.4 the statistical procedure to define the sensitivity limit of the analysis is introduced in quite some detail. This procedure is then used in section 7.5 to summarise the measurement as a lower limit on the mass of the SM Higgs boson. In that section also an evaluation of the systematic uncertainties and possible improvements to the analysis are presented. The combined result from the LEP experiments is discussed and in the last two sections the search for the Higgs boson in the near future is quickly reviewed before ending with a summary and conclusion.

7.1 Extending the probability computation

Although the mass of the Higgs boson is not predicted within the SM, the SM does predict the properties of the Higgs boson as a function of its mass. As described in section 2.4 for a given Higgs mass not only the branching fraction into a pair of b-quarks is precisely predicted, but also the production cross section is known once a specific centre-of-mass energy is defined. Using the generated Monte Carlo samples, also the hadronic pre-selection efficiencies for the event selection described in section 4.5.2 are known at each centre-of-mass energy as a function of the Higgs boson mass. For Higgs masses close to the kinematic limit these are around 90% as can be seen in figure 4.13 for a centre-of-mass energy of 200 GeV. All properties of the Higgs signal needed as inputs in the expression to compute the compatibility with a Higgs signal, equation (5.15) are therefore known.

In this analysis these dependencies of final state characteristics on $M_H$ are taken into account, analytically where possible. This results in an optimal sensitivity to a possible signal by incor-
porating in a consistent way the known (varying) differences between the ZH signal and SM background for a varying Higgs mass hypothesis.

An extension of the existing probability computation, compared to that used to measure the NC02 cross section (chapter 6), is required since in ZH production there are two bosons with different characteristics in the final state. The ambiguity that is present in a 4-jet ZZ or W^+W^- event, due to the possible jet-pairings, now doubles since in each pairing there is an additional ambiguity: each di-jet can be either the Higgs or the Z boson. Before discussing the performance of the analysis in separating the Higgs signal from the SM background in section 7.3, first the use of mass information is discussed.

## 7.2 Extracting mass information

The method to assign a compatibility for a pair of di-jets with a Higgs hypothesis using only mass information is described in section 7.2.2 and is a natural extension of the ideogram method described in section 5.2.3. To introduce some of the difficulties connected to mass reconstruction in these final states and to justify the choice for using the ideogram method, first the 'standard' method to extract the Higgs mass information per event (a single Higgs mass estimator) is presented in section 7.2.1.

### 7.2.1 Fixing the Z mass to 91.2 GeV/c^2

In most analyses the procedure to find the Higgs mass in the event is the following: first decide on the correct jet-pairing\(^1\) (and assignment) representing the H and the Z (often the pairing with the two most b-quark like jets is defined as the Higgs) and then use the knowledge of the Z mass to improve the resolution on the reconstructed Higgs mass. In this section some of the properties and features of the last step in this procedure are discussed. To eliminate the effect of the first step in this procedure a Monte Carlo study (without ISR radiation) is performed in the (ideal) case in which both the correct pairing and assignment are known. The results on the reconstructed Higgs masses using this procedure are compared to those where the Z mass is left free.

The effect of the constrained fit (requiring the reconstructed event to satisfy energy and momentum conservation as described in section 4.3) on the estimation of the Z boson mass is shown in figure 7.1. The ZH events used to make this distribution were generated at a centre-of-mass energy of 200 GeV for a Higgs mass of 85 GeV/c^2. After this 4C-constrained fit, the starting point of each analysis, not only is the mean value of the reconstructed Z mass close to \(m_Z\) (91.2 GeV/c^2), but also the resolution is significantly improved compared to the one using directly the reconstructed jets. At this stage the resolution on the Z mass is however still much larger than the intrinsic width of the Z (\(\Gamma_Z=2.49\) GeV/c^2).

The (standard) procedure to improve the precision on the estimation of the Higgs mass is to fix the Z boson mass to its pole mass of 91.2 GeV/c^2 and fit the event again. This type of fit is called a 5C(b)-fit, where in addition to requiring energy and momentum conservation (4C-fit), there is

---

\(^1\) Note that these problems are only present in the 4 quark and (part of) the \(q\bar{q}\tau^+\tau^-\) final states.
Figure 7.1: The reconstructed Z boson mass (before and after the 4C-constrained fit) compared to the generated Z boson mass in ZH events in the ideal case that the correct jet-pairing is known. Events were generated at a centre-of-mass energy of 200 GeV and the Higgs mass was 85 GeV/c^2. The widths for the reconstructed Z mass distributions are defined as the σ's from a Gaussian fit.

an additional constraint: for a given pairing one of the di-jet masses is known and equal to M_{hyp} (in this case 91.2 GeV/c^2).

\[ \sum_{i=1}^{n_{jets}} p_i^{(fitted)} \mu = (0, 0, 0, \sqrt{s}) \quad \& \quad \text{for this pairing } M_{ij} = M_Z \]  

(7.1)

The 5C(b)-fit is an ideal tool to estimate and improve the resolution on the unknown Higgs mass in case the Z boson mass in the event is described by a Breit-Wigner with a pole mass of 91.2 GeV/c^2 (hatched distribution in figure 7.1). For a wide range of (light) Higgs masses this is indeed the case, but when the sum of the Higgs mass and the Z mass gets close to the kinematic limit, the requirement of a Z mass distribution according to a Breit-Wigner is no longer fulfilled. The distribution of the mass of the Z boson in the event is truncated at M_Z = \sqrt{s} - M_H as is illustrated in the left plot of figure 7.2. In that plot the (normalised) Z mass distribution for two different values of the Higgs mass is shown at a centre-of-mass energy of 200 GeV.

The effect of the varying shape of the Z mass distribution on the reconstructed Higgs mass using the 5C(b)-fit is shown in the right plot of figure 7.2. For Higgs masses (much) smaller than \( \sqrt{s} - 91.2 \) GeV/c^2, fixing the Z mass to its pole mass results indeed in an increased precision in the estimation of the Higgs boson mass. For a Higgs mass close to (or above) \( \sqrt{s} - 91.2 \) GeV/c^2 however, this procedure not only results in a bias on the reconstructed Higgs mass (the sum of
the $Z$ and the Higgs mass can not exceed $\sqrt{s}$, but also the reconstructed mass distribution is very asymmetric and its width can no longer be interpreted as the resolution on the true Higgs mass.

![Generated Z mass vs. Reconstructed Higgs mass](image)

Figure 7.2: The left plot shows the (normalised) mass distribution for the generated $Z$ boson when pair-produced with a Higgs boson for two different Higgs masses. The right plot shows the reconstructed Higgs boson mass (for the same two Higgs masses) using two methods: the shaded histogram represents the method when the $Z$ mass is not used at all and the hatched histogram the one where the $Z$ mass is fixed to to 91.2 GeV/c$^2$.

To follow the effect of this kinematic feature as a function of the true Higgs mass, the (mean) reconstructed Higgs mass is shown as a function of the true Higgs mass in the left plot of figure 7.3. When the $Z$ mass is left free there is no bias on the reconstructed Higgs mass over the full range of true Higgs masses as is indicated by the shaded band. Using the fixed $Z$ mass as constraint (represented by the hatched band), there is an increased bias in the mean of the reconstructed Higgs mass distribution as the true Higgs mass increases. For Higgs masses above $\sqrt{s} - 91.2$ GeV/c$^2$ the bulk of the reconstructed masses remains very close to the kinematic limit (illustrated by the dashed line representing the most likely reconstructed Higgs mass), but the reconstructed mass distribution has a more prominent tail resulting in an apparent 'reflection' off the kinematic limit for the mean reconstructed mass.

**The resolution on a reconstructed Higgs mass versus the resolution on the true Higgs mass**

The resolution on the reconstructed Higgs mass for a specific Higgs mass (distributions as in the right plot of figure 7.2) should not be confused with the resolution on the true Higgs mass given a specific reconstructed Higgs mass. These two numbers are identical only for light Higgs masses. When the sum of the $Z$ mass and the Higgs mass is close to the kinematic limit, the uncertainty on the sum(difference) of the $Z$ mass and Higgs mass becomes very small(large) as was shown already in section 5.2.2. Fixing the $Z$ mass in these events will result in an artificially (too) small

---

2 Reflecting the flattening (Breit-Wigner) tail of the $Z$ boson mass distribution.
error estimate on the reconstructed Higgs mass. The uncertainty becomes (much) smaller than $\Gamma_Z$ and can no longer be interpreted as the resolution on the true Higgs mass.

An illustration of this feature is shown in the right plot of figure 7.3, where the probability density function for the true Higgs mass is shown for reconstructed Higgs masses between 103.0 and 104.0 GeV/c$^2$. Even for this intermediate Higgs mass the distribution already has a non-Gaussian shape. These effects will only increase for higher reconstructed masses as can also be understood from the left plot of figure 7.3, where the dashed line shows that for any Higgs mass above $\sqrt{s} - 91.2$ GeV/c$^2$ the most likely reconstructed Higgs mass will always be close to the kinematic limit.

![Figure 7.3: The left plot shows the mean reconstructed Higgs mass as a function of the true Higgs mass using two different methods (the width of the bands corresponds to the RMS of the reconstructed mass distribution). The shaded band represents the method where the Z mass is left free and the hatched band represents the procedure where the Z mass is fixed to 91.2 GeV/c$^2$ (the most likely reconstructed Higgs mass in this last procedure is indicated by the dashed line. The right plot shows the probability density function for the true Higgs mass (assuming $M_H < 115$ GeV/c$^2$) when the reconstructed Higgs mass is close to 103.5 GeV/c$^2$.](image)

When an excess in the reconstructed Higgs mass spectrum is observed close to the kinematic limit it is not the position of the peak, but the number of events in the peak that is most suitable to distinguish between various Higgs mass hypotheses since the relative ZH production cross sections for a Higgs boson with a mass of 110-112.5-115 GeV/c$^2$ (at a centre-of-mass energy of 206.7 GeV) are roughly 3:2:1.

### 7.2.2 Using Ideograms

To account for the varying expected mass distribution in this analysis the (ideogram) procedure defined in section 5.2.3 is used. This allows to compute per pairing (and assignment) a com-

---

3 Assuming the Higgs mass is below 115 GeV/c$^2$. 

compatibility with a specific Higgs mass hypothesis since instead of fixing the Z mass to its pole the (analytically known) distribution of the Z boson mass in ZH events is used in combination with the event-by-event experimental errors on the reconstructed masses. These assignment-compatibilities are the ideal way to take into account the increased ambiguity connected to the mass information. Since also the other event variables are predicted given a specific pairing and assignment, the mass information can easily be incorporated in the probability computation allowing a consistent compatibility of the event with various hypotheses to be constructed.

In ZH events (for a Higgs mass $M_H$) the probability density function of the masses of the two bosons can be described by the (normalised) product of a Breit-Wigner for the Z boson and a delta function for the Higgs boson$^4$. Adding a phase space factor the distribution is as in equation (5.4):

$$P_{\text{mass}}(m_1, m_2 \mid \text{hyp}) \propto BW(m_1 \mid m_{01}, \Gamma_{01}) \delta(m_2 - M_H) PS(m_1, m_2, s),$$  \hspace{1cm} (7.2)

To illustrate the separation power between ZH events and events originating from SM background processes, the distributions of event probabilities using only mass information are shown for the different event types in figure 7.4 for a Higgs mass of 90 GeV/c$^2$ (left plot) and 110 GeV/c$^2$ (right plot). These event 'mass-only' probabilities $P_{ZH(M_H)}$ are defined as in equation 5.9 at the end of section 5.2.3, where similar definitions were used to study the separation power between $ZZ$, $q\bar{q}(\gamma)$ and $W^+W^-$ events (see figures 5.6 and 5.7). Since $ZZ$ events have a similar mass distribution as ZH(90) events, the event probability can almost never exceed 0.5.

![Figure 7.4](image-url)

Figure 7.4: The normalised distributions of the relative probability per event to be compatible with a ZH event when using only mass information for SM background processes (hatched histogram) and signal (solid histogram). The left(right) plot is for a 90 (110) GeV/c$^2$ Higgs mass hypothesis.

$^4$ At masses below 120 GeV/c$^2$ the width of the Higgs boson is below 5 MeV/c$^2$ as can be seen in figure 2.6 and can be approximated by a delta function.
7.3 Probability distributions: characteristics & performance

Using the mass information as described in section 7.2.2 the event-by-event compatibility with a hypothesis of a Higgs boson with a specific mass can now be computed using the procedure described in section 5.4. Here, the characteristics and performance in the separation between signal and background are discussed.

In figure 7.5 the normalised distributions of the logarithm of the event-by-event probability are shown for a Higgs mass hypothesis of 90 GeV/c\(^2\) (left plot) and 110 GeV/c\(^2\) (right plot) for ZH events and for those originating from SM background processes. The additional distribution of the ZH(110)-probability for ZH(90) events (dashed line in the right plot) illustrates the fact that indeed the ZH(110)-probability computation is optimised for ZH(110) events, since the separation between the possible signal events and those originating from the SM background processes is clearly deteriorated.

As in the case of the ZZ analysis (see figure 6.6), for a given Higgs mass hypothesis, the background composition changes when going to lower efficiencies. In examining ZH events however, the dominant background (at a fixed efficiency) depends also strongly on the mass of the Higgs boson in the hypothesis as is illustrated in the two plots of figure 7.6. The agreement between observed and expected number of events is examined over a large range of ZH efficiencies by plotting the number of events (data and that expected from the SM with and without the hypothetical ZH signal) as a function of the corresponding ZH efficiency. These evolution plots are shown for a Higgs boson of 90 GeV/c\(^2\) (left plot) and 110 GeV/c\(^2\) (right plot). As expected, for a Higgs mass close to the Z mass the dominant background comes from ZZ events whereas for a Higgs mass of 110 GeV/c\(^2\) the main background is from q\(\bar{q}\)(\(\gamma\)) events.

For both the 90 GeV/c\(^2\) and 110 GeV/c\(^2\) Higgs hypothesis there is a good agreement between the number of observed events and the number of predicted events when there is no additional Higgs signal assumed to be present. As an indication of the separation power at the various Higgs hypotheses and the agreement between the number of expected and observed events (in the year 2000 data set) a few characteristic numbers are given in table 7.1 for a range of Higgs masses between 90 and 115 GeV/c\(^2\) at the point where the product of efficiency and purity is maximal.

From table 7.1 it is clear that the observed data in the 205-207 GeV data set are best explained by the SM predictions without an additional Higgs signal over the full range of Higgs boson masses, although for a Higgs signal at 115 GeV/c\(^2\) there is not enough separation power to reject the hypothesis that there was actually a signal present. The next section is devoted to describing the method used by all the LEP experiments to determine which hypothetical signal can be excluded at a predefined confidence level and thereby allowing, within the framework of the SM prediction, the measurement to be summarised by a lower limit on the mass of the Higgs boson.
Figure 7.5: Expected normalised distributions of the $ZH$-probability at a centre-of-mass energy of 206.7 GeV for $ZH$ events (solid histograms) and the SM background processes (hatched histograms). The left plot shows the separation between $ZH$ signal and SM background for a Higgs of 90 GeV/$c^2$ whereas the right plot shows the distributions for a 110 GeV/$c^2$ Higgs. The dashed line in the right plot shows the distribution for a $ZH(90)$ signal.

Figure 7.6: Number of expected events left for various processes as a function of the efficiency for $ZH$ events with a 4-quark final state in the combined year 2000 data set. The number of events observed in the data is represented by the points and compared to the expected number of events with and without an additional Higgs signal. The left plot is for $ZH(90)$ events whereas the right plot shows the distributions for a 110 GeV/$c^2$ Higgs.
Table 7.1: The number of observed events with a ZH-probability above the value for which the product of efficiency and purity is maximal, is compared to the SM prediction (efficiencies are given in %). Note that the probabilities are the ones optimised for the corresponding Higgs mass hypothesis. The number of predicted ZH events is also given. A good agreement between data and the SM prediction (without an additional ZH contribution) is observed for all mass hypotheses.

<table>
<thead>
<tr>
<th>$M_H$ (GeV/c$^2$)</th>
<th>$\ln(P_{ZH})$</th>
<th>$\epsilon(ZH)$</th>
<th>$ZH$</th>
<th>SM(no ZH)</th>
<th>observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>-2.22</td>
<td>41.3</td>
<td>27.02</td>
<td>41.90</td>
<td>41</td>
</tr>
<tr>
<td>95</td>
<td>-3.13</td>
<td>57.2</td>
<td>31.74</td>
<td>80.57</td>
<td>69</td>
</tr>
<tr>
<td>100</td>
<td>-2.22</td>
<td>46.4</td>
<td>21.34</td>
<td>31.21</td>
<td>28</td>
</tr>
<tr>
<td>105</td>
<td>-2.12</td>
<td>43.7</td>
<td>15.22</td>
<td>19.68</td>
<td>18</td>
</tr>
<tr>
<td>110</td>
<td>-2.43</td>
<td>41.8</td>
<td>9.09</td>
<td>13.78</td>
<td>13</td>
</tr>
<tr>
<td>115</td>
<td>-3.03</td>
<td>28.4</td>
<td>1.64</td>
<td>4.82</td>
<td>4</td>
</tr>
</tbody>
</table>

7.4 Probing the sensitivity limits

Probing the sensitivity limits and interpreting the (negative) result from a search as a limit on a hypothetical physics parameter is common practice in search analyses performed in (particle) physics experiments. In the case of the search for the SM Higgs boson for example the result of the measurement, as an answer to the question “Is there a Higgs boson?”, can not be summarised with a simple 'yes' or 'no', since (as can be seen from table 7.1) the experiment has no sensitivity to positively exclude nor to confirm the presence of a signal of a heavy Higgs boson.

In this section the procedure to determine the sensitivity limit of the analysis is introduced and applied to the analysis of the search for the SM Higgs boson. The result from a single measurement (for a specific Higgs mass) will be analysed in the form of hypothesis testing, where the null hypothesis is the one in which the signal is absent (background-only) and the alternate hypothesis is the one where the Higgs signal is present (signal+background). The method used to interpret the measurements is then the $\text{CL}_s$ (or modified frequentist) procedure [80] that is used by the LEP collaborations to analyse and summarise their combined results.

In section 7.4.1 a general introduction of the method is given and the test statistic, used to rank experiments from most background-like to most signal+background-like, is defined. Then the method to quantify the degree to which various hypotheses are favoured or excluded, given a specific measurement, is formally introduced. Within this framework a definition of the sensitivity reach of the measurement is given. In section 7.4.2 the method is applied to summarise the results from the search for the SM Higgs boson in the fully hadronic final state. The obtained sensitivity limit is finally interpreted (within the SM) as a lower limit on the mass of the Higgs boson in section 7.5.1.

7.4.1 General definition of the test statistic and confidence levels

The first step in assessing the separation power of the analysis in distinguishing between the two hypotheses is to construct a single variable that can be used to rank experiments from most

---

5 The ALEPH collaboration uses a slightly different method [81] to present its individual result.
background-like to most signal+background-like. This variable is called the test statistic. A sensible choice is to define it as (a function of) the likelihood ratio between the two hypotheses since such a definition possesses the property that it allows the measurement to confirm as strongly as possible a signal when it exists or to exclude it as strongly as possible in its absence. The test statistic ($X$) is here defined as:

$$X = -2\ln(Q), \text{ with } Q = \frac{L_{s+b}}{L_b},$$

(7.3)

where $L_{s+b}$ is the likelihood for the signal+background hypothesis and $L_b$ is the likelihood for the background-only hypothesis. In this way, $X$ is constructed to increase monotonically for increasingly background-like measurements: low-$X$ is signal+background-like and high-$X$ is background-like. The probability density function for $X$ for 'gedanken' background-only experiments is defined as $P_b(X)$ and for signal+background experiments the probability density function is given by $P_{s+b}(X)$.

To visualise the various definitions derived from the distributions of $P_b(X)$ and $P_{s+b}(X)$ the two probability density functions are shown in figure 7.7. The sensitivity of a measurement is given by the effective separation of the two distributions which is given by a combination of the intrinsic separation power of the analysis and the amount of collected statistics. Note that the experimental data produce only a single value for $-2\ln(Q)$ denoted as $X_{obs}$. For this value one can define compatibilities with either of the two hypotheses.

Compatibility with the background-only hypothesis

For a given experimental observation ($X_{obs}$) the confidence level in the background hypothesis ($\text{CL}_b$) is given by the probability that a background-only experiment has a value for $X$ that is larger or equal to $X_{obs}$. Therefore the probability that a background-only experiment is more background-like than the observed measurement can be formally written as:

$$\text{CL}_b = P_b(X \geq X_{obs}) = \int_{X_{obs}}^{\infty} P_b(X) \, dX$$

(7.4)

From this definition (see also figure 7.7) it is clear that $1-\text{CL}_b$ defines the probability that a background-only experiment looks more signal+background-like than the one observed in this measurement (the probability to observe an even larger fluctuation towards the signal region in case there is no signal present). For background-only experiments, by definition, $1-\text{CL}_b$ is on average $\frac{1}{2}$ whereas for the average signal+background experiment $1-\text{CL}_b$ is (very) small (in case the two distributions are well separated).

Compatibility with the signal+background hypothesis

Similar, for a given experiment the confidence level in the signal+background hypothesis is given by the probability that the test-statistic $X$ from a signal+background experiment is larger than $X_{obs}$. Again, this can be interpreted as the probability that an experiment, in case there is indeed a signal present, looks more background-like than the observed measurement. Analogous to equation (7.4) it can be written as:
Higgs production (SM Higgs decay)

\[ CL_{s+b} = P_{s+b}(X \geq X_{\text{obs}}) = \int_{X_{\text{obs}}}^{\infty} P_{s+b}(X) \, dX \quad (7.5) \]

For the average signal+background experiment, by construction, \( CL_{s+b} = \frac{1}{2} \) whereas for the average background-only experiments this value will be very small (again under the assumption that the two distributions are well separated) as can be understood from figure 7.7.

*Figure 7.7: Definition of the various confidence levels used in the analysis of testing the compatibilities with both a background-only and a signal+background hypothesis.*

**Compatibility with the signal hypothesis**

Interpretation of the difference between the number of expected and observed events as an estimation of the signal rate can lead to controversial results in measurements where there is no clear separation between the background and signal+background hypotheses (e.g. in case of a very low expected signal rate). When for example less events are observed than expected from background this can be interpreted as a negative signal cross section even to the point where a zero cross section is excluded at the 95% CL when the 'standard' methods of inference are applied. To deal with these difficult regions (the region where the limit is to be set is by definition the region where the experiment loses sensitivity) the confidence level in the signal+background hypothesis (\( CL_{s+b} \)) is modified by normalising it to the confidence level for the background-only hypothesis (\( CL_b \)). The (modified frequentist) *confidence level in the signal* is therefore defined as:

\[ CL_s = CL_{s+b} / CL_b \quad (7.6) \]
Note that CL$_{S}$ is not a real confidence, but rather a ratio of confidences. Using this modified definition of the signal confidence allows to obtain sensible exclusion limits even when the observed rate is so low that the background hypothesis is called into question. The exclusion limits obtained using this modified definition are therefore always conservative. This method of assessing the sensitivity limit is known as the Modified Frequentist method.

**Rules for discovery and exclusion**

For a discovery the null hypothesis has to be rejected. To do that the 'incompatibility with the background-hypothesis' (1-CL$_{b}$) is used. It is the probability that a background-only experiment fluctuates towards the signal region as much as in the observed measurement or more. The values for 1-CL$_{b}$ can be transformed into standard deviations using a (one-sided) Gaussian approximation (see table 7.2). A discovery can be claimed when 1-CL$_{b}$ is smaller than 5.7x10$^{-7}$, a so-called 5$\sigma$-effect.

<table>
<thead>
<tr>
<th>1-CL$_{b}$</th>
<th>size of effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7x10$^{-3}$</td>
<td>3$\sigma$ (evidence)</td>
</tr>
<tr>
<td>5.7x10$^{-7}$</td>
<td>5$\sigma$ (discovery)</td>
</tr>
</tbody>
</table>

Table 7.2: Conversions of values for 1-CL$_{b}$ into one-sided Gaussian fluctuations.

A signal hypothesis will be considered excluded at a given CL when:

$$1 - \text{CL}_S < \text{CL}$$

(7.7)

The lower limit on the Higgs boson mass obtained using the CL$_{S}$ method should be interpreted as the sensitivity boundary of the experiment. This means, the boundary of a region where one would not have expected the signal (in case the signal exists) to fluctuate downward as much as in the actual measurement. In case of the search for the Higgs boson the lower limit on the Higgs mass is defined as the highest mass whose corresponding ZH signal can still be excluded at the 95% CL. This can be interpreted as the Higgs mass for which the probability that the signal fluctuated downward to the measured value (or more) is still smaller than 5% in case the signal exists.

Once the definitions of exclusion and discovery are given the method can be applied on the analysis of the search for the Standard Model Higgs boson as presented in this thesis.

**7.4.2 Application of the CL$_{S}$ method to a single channel Higgs search**

Applying the CL$_{S}$ method on the results from the analysis presented in section 7.3 requires the construction of a test statistic as in equation (7.3). For a given Higgs mass the best separation between the background-only and background+signal hypothesis is obtained by using the probability distributions as a separating variable (where signal and backgrounds have been normalised to equal luminosity).
One of the possibilities to construct the likelihood ratio of the two hypotheses is to perform a simple (Poisson) counting experiment for events above the value of the ZH-probability that provides optimal statistical sensitivity (see table 7.1). An improved sensitivity is obtained however by using the shape of the probability distribution for the two hypotheses. Using this approach the likelihood ratio \((Q = L_{s+b}/L_b)\) between the signal+background and the background-only hypothesis can be written as:

\[
Q = \frac{e^{-(s+b)}(s + b)^{n_{\text{obs}}}}{e^{-b} b^{n_{\text{obs}}} / n_{\text{obs}}^!} \cdot \frac{\prod_{i=1}^{n_{\text{obs}}} s S(p_i) + b B(p_i)}{\prod_{i=1}^{n_{\text{obs}}} B(p_i)}
\]

(7.8)

\(S(p)\) and \(B(p)\) are the probability density functions for the ZH-probability for signal and background events respectively. The most background-like part of the ZH-probability distribution is not used when computing \(Q\) and in expression (7.8) therefore \(n_{\text{obs}}\) is the number of observed events and \(s\) and \(b\) are the number of expected signal and background events with \(\text{ln}(p_i) > -3.5\).

Restricting to a reasonably pure part of the probability distribution does not reduce the sensitivity to the signal and is done to avoid potential large systematic effects from background processes (as was shown in section 6.4.1 for the ZZ cross section measurement). Expression (7.8) can be simplified to:

\[
Q = e^s \prod_{i=1}^{n_{\text{obs}}} \left(1 + \frac{s S(p_i)}{b B(p_i)}\right)
\]

(7.9)

and the test statistic \(-2\ln(Q)\) (as defined in (7.3)) can be expressed as a sum of weighted events:

\[
-2\ln(Q) = 2s - 2 \sum_{i=1}^{n_{\text{obs}}} \ln \left(1 + \frac{s S(p_i)}{b B(p_i)}\right)
\]

(7.10)

In this expression \(1 + \frac{s S(p_i)}{b B(p_i)}\) is the relative probability of an event with ZH-probability \(p_i\) to have originated from an experiment where there was signal+background to a background-only experiment: the likelihood ratio.

Computing the distributions for \(-2\ln(Q)\) for 'gedanken' background-only and signal+background experiments and obtaining the value of \(-2\ln(Q)\) in the data \((X_{\text{obs}})\) requires the correct weight for each event to be determined. The weight for each event is parametrised as a function of the ZH-probability \((p_i)\) using the ZH-probability distributions from a large number of Monte Carlo background and signal events. As an example this is shown in the right plot of figure 7.8 for a Higgs boson of 110 GeV/c^2. In the left plot the original ZH-probability is shown for the two hypotheses in the pure ZH region (solid histogram is background-only and the open histogram represents the expectation in case there is also a ZH signal present).

To obtain the probability density functions for the signal+background and the background-only 'gedanken' hypotheses, a large number of 'gedanken' experiments have been performed by drawing a (Poisson) number of events from the distribution around the expectation corresponding to the luminosity as collected in the data.
Figure 7.8: The left plot shows the distribution of the logarithm of the \( ZH(110) \)-probability above -3.5 for SM background (solid histogram) and the expectation with the additional \( ZH(110) \) contribution (open histogram). The right plot shows the ratio of the signal+background and the background-only distribution (event weight) and its parametrisation (solid line).

### 7.4.3 Example: results for a Higgs boson with a mass of 110 GeV/c²

For a Higgs mass of 110 GeV/c² the probability density functions for the test-statistic for background-only and signal+background experiments, obtained from a large number of 'gedanken' experiments, are given in figure 7.9. For the background-only experiments the one and two standard deviations are given and also the observed value of \( -2\ln(Q) \) is shown. The observation is clearly background like. The characteristics of these two distributions are given in the first two rows of table 7.3 as expected results for the average background-only and signal+background experiment.

The expected 1-\( \text{CL}_{b} \) for the average signal+background experiment is 0.003, far away from \( 5.7 \times 10^{-7} \) indicating that if the signal is there it is not expected to be discovered (a 5\( \sigma \) effect as defined in table 7.2). On the other hand, since the \( \text{CL}_{s} \) for the average background-only experiment is smaller than 0.05 (0.016, see first row of table 7.3) the signal corresponding to this Higgs boson mass is expected to be excluded. With an observed \( \text{CL}_{s} \) of 0.008 it is also excluded (at 95% CL).

<table>
<thead>
<tr>
<th></th>
<th>( 1-\text{CL}_{b} )</th>
<th>( \text{CL}_{b} )</th>
<th>( \text{CL}_{s+b} )</th>
<th>( \text{CL}_{s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>average background-only experiment</td>
<td>0.500</td>
<td>0.500</td>
<td>0.008</td>
<td>0.016</td>
</tr>
<tr>
<td>average signal+background experiment</td>
<td>0.003</td>
<td>0.997</td>
<td>0.500</td>
<td>0.502</td>
</tr>
<tr>
<td>observed in year 2000 data</td>
<td>0.698</td>
<td>0.302</td>
<td>0.002</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Table 7.3: A summary of the characteristics for the analysis searching for a Higgs boson with a mass of 110 GeV/c². Apart from the expected numbers for the average background-only and signal+background 'gedanken' experiment also the observed values in the year 2000 data set are given.
7.5 Results

In this section the results from the search for the SM Higgs boson are presented. The result from the 4-quark final state is given in section 7.5.1. Since the main focus is on the maximum Higgs mass that can be excluded, only the year 2000 data set is used. The sensitivity of the data sets at centre-of-mass energies below 205 GeV is marginal for large Higgs masses, therefore the Higgs compatibilities and corresponding results are evaluated up to Higgs masses of 115 GeV/$c^2$. The (combined) results from the four LEP experiments are presented in section 7.5.3. These results use the full LEP2 data set and hence provide the most stringent (expected) limit on the mass of the Higgs boson.

7.5.1 Results for the 4-quark final state

The distribution of the probability density functions of the test-statistic for the two hypotheses at Higgs masses of 100, 105, 110 and 115 GeV/$c^2$ are constructed using a procedure similar to the one defined in the previous section. These distributions are shown in figure 7.10 where also the observed values for $-2\ln(Q)$ in the data are indicated. In order for the background-only hypothesis to be compared to the signal-background hypothesis for an arbitrary Higgs mass ($M_H$) a procedure has to be defined to construct the distributions for the test-statistic at that specific mass. In this section both this method and the one used to determine the evolution of the observed values in the data are discussed. At the end of this section the analysis is summarised by interpreting the results as the (expected and observed) lower limit on the mass of the SM Higgs boson.
Figure 7.10: The probability density functions for the test-statistic for background-only and signal+background experiments for hypotheses where the Higgs mass is 100 GeV/c^2 (top left plot), 105 GeV/c^2 (top right plot), 110 GeV/c^2 (bottom left plot), 115 GeV/c^2 (bottom right plot). The observed values at each of these Higgs mass hypotheses, using the year 2000 data set, are indicated by \( X_{\text{obs}} \).

**Expected -2ln(Q) distribution as a function of \( M_H \)**

The expected -2ln(Q) distributions for a given Higgs mass (\( M_H \)) are interpolated from those corresponding to the neighbouring two mass hypotheses that are known from Monte Carlo studies (figure 7.10). This is done for background-only and signal-background experiments separately. The shape of the test-statistic for an intermediate Higgs mass is constructed as a weighted average of the shapes of the two neighbouring distributions, with weights inversely proportional to the distances (in mass) between the intermediate Higgs mass and that of the neighbouring distributions.
Since the interpolation is only over a few GeV/c², the mean position of the distribution behaves to first order similar to the change in effective ZH cross section in the selected pure-ZH region. Using the known ZH cross section and the assumption that the selection efficiency changes smoothly over this mass range the mean value is found. The resulting expected $-2\ln(Q)(M_{H})$ distributions are shown in the left plot of figure 7.11. In that plot the central position of the background-only (signal+background) distribution is indicated by the solid(dashed) line. For the background-only hypothesis the width of the distribution is indicated by the shaded areas (1 and 2 sigma).

**Observed $-2\ln(Q)$ distribution as a function of $M_{H}$**

The observed values for $-2\ln(Q)$ for an arbitrary Higgs mass hypothesis can not be obtained from the observed values at the neighbouring mass points for which the full ZH-probability distributions have been computed. In order to set a 'confident' confidence limit, a precise determination of the observed values in the (mass) region where the limit is expected is needed. These values can be obtained without having to repeat the full analysis at many different Higgs masses as is described below. For both expectation and observation the $-2\ln(Q)(M_{H})$ distributions are translated into $1-\text{CL}_{b}(M_{H})$ values. The results are shown in the right plot of figure 7.11.

![Figure 7.11: Results from the search for the SM Higgs boson in the fully hadronic final state using the year 2000 data set. The left plot shows the evolution of the $-2\ln(Q)$ distribution for the background-only (solid line) and the signal+background-hypothesis (dashed line). The observed values in the data are indicated by the connected dots. The right plot shows the corresponding distribution of $1-\text{CL}_{b}$ for both hypotheses and the data.](image)

For Higgs masses between 100 and 115 GeV/c² extra ideogram compatibilities (mass-only information compatibilities per-pairing and assignment) have been computed at 1 GeV/c² intervals. Using these mass compatibilities the ZH probabilities can be computed for the corresponding Higgs masses since the other components entering the expression for the ZH-probability (as in expression 5.17) are either known as a function of the Higgs mass or are not (or only slightly) dependent on the Higgs mass. Each of these ZH-probability distributions for the data can be con-
converted into a single observed value for $-2\ln(Q)$ without the use of dedicated Monte Carlo samples to study the background and signal distributions in the ZH-probability distribution. This conversion is possible since the probabilities are defined in such a way that the parametrisation used to compute the event weights $\left(1 + \frac{e^{p_{j}}}{b(p_j)}\right)$ as shown in figure 7.8 for a Higgs mass of 110 GeV/c$^2$) is almost identical for all Higgs masses. This characteristic allows the event weight to be computed for each data event. The sum of the weights for the events in the pure-ZH region can be converted into a value for $-2\ln(Q)$ using formula 7.10. The observed values of $-2\ln(Q)(M_{H})$ in the data are shown in figure 7.11 were they are indicated (as in future plots) by connected points.

**CL$_S$ as a function of $M_{H}$ and extracting a lower limit on the Higgs mass**

The distribution of the signal confidence as a function of the Higgs mass, $\text{CL}_S(M_{H})$, is shown in figure 7.12 for the background-expectation (solid line) and the signal+background (dashed line) hypothesis. The 1$\sigma$ uncertainty for the background-only experiments is indicated by the shaded area. As defined at the end of section 7.4.1 a Higgs mass hypotheses for which $\text{CL}_S < 0.05$ can be excluded at 95%CL.

![Figure 7.12: Distribution of the signal confidence CL$_S$ for the background-only and the signal+background hypotheses. The shaded area indicates the 1$\sigma$ uncertainty for the background-only experiments. The observed values in the year 2000 data set are also shown.](image)

Using the intersection point at 0.05 the full measurement can be summarised as a 95% CL lower limit on the mass of the SM Higgs boson:

Expected: $M_{H} > 112.0$ GeV/c$^2$ (at 95% CL)

Observed: $M_{H} > 112.2$ GeV/c$^2$ (at 95% CL)
7.5.2 Systematic uncertainties and possible further improvements

In this section the uncertainty on the predicted background level is estimated and its effect on the expected and observed lower bound of the mass of the SM Higgs boson is evaluated. Finally some suggestions are given to improve the sensitivity of the analysis to a possible Higgs signal.

Systematic uncertainties

The search for the Higgs boson is a cross section measurement of a (very) small signal. In the region where the experiment loses sensitivity effectively only a handful of signal and background events remain. The statistical fluctuations are large and are absorbed in the definition of the lower limit on the mass of the Higgs boson. The systematic uncertainties are often small compared to the statistical uncertainties and are not expected to strongly affect the results. For counting experiments an analytic treatment to incorporate systematic uncertainties in an upper/lower limit is discussed in [82], but for more complex analyses the effect is evaluated using a more rigorous Monte Carlo approach.

As was shown in section 7.3, the background decomposition at high signal purity changes as a function of the Higgs mass in the hypothesis. For a 90 GeV/c² Higgs, the main background originates from Z boson pair production, but above 100 GeV/c² the dominant background is from q̅q(γ) events. This is illustrated in figure 7.13 where the relative background decomposition is shown as a function of the Higgs mass hypothesis at the point of optimal statistical sensitivity.

![Figure 7.13](image)

Figure 7.13: This plot shows the (relative) background decomposition as a function of the Higgs mass in the hypothesis at the point where the product of efficiency and purity is maximal.

The uncertainty on the predicted SM background level is therefore mainly coming from the uncertainty in the q̅q(γ) cross section (7%). The effect from the uncertainty on the gluon splitting rate into a b̅b-pair on the background cross section is 3% and the uncertainty in the parametrisation of the b-tag likelihood ratios per jet (using a similar procedure as in 6.4.5) induces a maximum
change in the background level of 6%. The combined uncertainty on the background level is therefore conservatively estimated to be around 10%.

The procedure defined in section 7.5.1 to find the maximum Higgs mass that can be excluded at 95% CL is repeated with a background cross section that has been increased by 10%. This corresponds to a reduced sensitivity of 350(100) MeV/c\(^2\) for the expected (observed) lower limit on the mass of the SM Higgs boson.

Possible further improvements

The analysis presented in this thesis is simultaneously optimised to identify ZH, ZZ, W\(^+\)W\(^-\) and q\(\bar{q}\)(\(\gamma\)) events. It is therefore not only good in identifying signal-like events, but also in rejecting those events that are also compatible with a background hypothesis. Possible improvements to increase the sensitivity for a Higgs signal are presented below. They are similar to those suggested to improve the ZZ cross section measurement (see section 6.7), although with different emphasis:

- **Improved rejection of q\(\bar{q}\)(\(\gamma\)) events:**
  An improved rejection of q\(\bar{q}\)(\(\gamma\)) events (the dominant background) could be achieved by using a more complex topological variable than the D\(_{pur}\) variable. Implementation of a (more) complex topological variable induces correlations with the extracted mass information, but these effects are expected to be small compared to the gain in sensitivity due to the elimination of a large fraction of the q\(\bar{q}\)(\(\gamma\)) events.

- **Quark-flavour tagging:**
  An improvement in solving pairing ambiguities can be achieved by using a more complex b-tagging algorithm that allows to (partially) separate b-quarks from anti-b-quarks. Using this information (b\(\bar{b}\),b\(\bar{b}\))-pairings can be favoured over (b\(\bar{b}\),b\(\bar{b}\)) ones. Resolving these ambiguities in a 4 b-quark event is more important for ZH events than for ZZ events, since in almost 20% of ZH events there are 4 b-quarks present compared to only 5% for ZZ.

- **Using boson angular distributions**
  Since the Higgs is a scalar particle, the angular distribution of the two bosons in ZH events is different from that produced in ZZ or W\(^+\)W\(^-\) events. This is shown in figure 7.14 where the absolute value of the cosine of the polar angle of both bosons is shown for ZZ, W\(^+\)W\(^-\) and ZH events at a centre-of-mass energy of 207 GeV. At the level of the pairing the corresponding angles of the constructed bosons can be used to disfavour an angular region that is more compatible with either a W\(^+\)W\(^-\) or ZZ region. Note that in the case of W\(^+\)W\(^-\) events also the charge of the bosons can be used to reduce their contribution to the total background.

7.5.3 Combined LEP results

Using the CL\(_{s}\) method, the results from the fully hadronic final state can easily be combined with those from other channels, since additional search channels can be incorporated in the expression for the likelihood ratio. The general expression for Q can be written (see equation 7.9 for a single channel) in the most general way as:
Higgs production (SM Higgs decay)

Figure 7.14: The distribution of the absolute value of the cosine of the polar angle for bosons in ZZ, W⁺W⁻, and ZH(115) events at a centre-of-mass energy of 207 GeV.

\[ Q = e^{-g} \prod_{j=1}^{n_{\text{chan}}} \prod_{i=1}^{n_{\text{bino}}} \left( 1 + \frac{s_j S(p_{ij})}{b_j B(p_{ij})} \right) \]  

(7.11)

In this expression \( j \) defines the search channel\(^6\). The test-statistic \(-2\ln(Q)\) can therefore again be written as a sum of weighted events as in equation (7.10), where each channel contributes to the final result with the combined weight of its selected events. The results from the four LEP experiments can be combined in a similar way as they can simply be seen as separate search channels. A detailed analysis of the results obtained using the full LEP2 data set can be found in various publications of the LEP Higgs Working Group (for example [83] for the results up to the summer of 2001). A short summary of the main results\(^7\) is given below.

The combination of the results from all LEP experiments, using the full LEP2 data set and all search channels, results in a distribution of \(-2\ln(Q)\) as a function of the Higgs mass as shown in the left plot of figure 7.15, displaying the LEP combined sensitivity to a Higgs signal. Contrary to the results from the analysis presented in this thesis, the LEP combined results show an excess in number of observed events compared to the background expectation. This excess is compatible with a ZH signal where the mass of the Higgs boson is equal to 115.6 GeV/c\(^2\). The two \(-2\ln(Q)\) distributions corresponding to this specific Higgs mass (a slice in the left plot at this specific mass) are shown in the right plot of figure 7.15. Given these distributions, the probability that a background-only experiment results in a similar value of \(-2\ln(Q)\) or even more signal-like is 3.4%: 1-CL\(_b\) = 0.034.

\(^6\) The search channels for ZH events are all decay modes where the Higgs boson decays hadronically and the Z boson either decays into a quark anti-quark pair (\(~70\%)\), a pair of neutrinos (\(~20\%)\) or a lepton pair (\(~10\%)\). Also the channel in which the Higgs decays into a pair of tau leptons and the Z boson decays hadronically is used.

\(^7\) All results quoted here are preliminary and represent the status at the time of the 2001 summer conferences.
With a 1-CL$_b$ of 0.034 (a 2.1σ effect), the combined LEP measurement indicates a hint of a possible Higgs signal being present in the data. However, this signal compatibility is not the combined effect of four experiments each supporting a signal+background hypothesis. From the two most sensitive experiments, ALEPH and DELPHI, the results from DELPHI clearly favour a background-only explanation of the observed data whereas the ALEPH data are very signal+background-like. As an indication of the sensitivity of the individual LEP experiments in combination with their actual measurements, the expected limits and observed 1-CL$_b$'s are shown in table 7.4 for various combinations of channels and experiments.

From these numbers it is clear that the signal-like interpretation of the data is most clearly favoured by the results from the (fully hadronic final state in the) ALEPH experiment. It should be noted that this channel is one of the most sensitive channels in LEP and that, if the measurement is interpreted as a Higgs signal, the obtained result in the ALEPH experiment is compatible with almost a 2σ upward fluctuation of a ZH(115.6) signal (as is indicated by a CL$_{s+b}$ of 0.94). The DELPHI experiment on the other hand observed less events than expected from background alone. This downward fluctuation is quite strong and the probability that a Higgs signal, if it exists, would result in a measurement that was even more background-like is only 2%. When all LEP experiments are combined, still a preference for a signal+background interpretation remains. A clear, but to many people unsatisfactory result: when DELPHI is left out from the combination there is a strong preference for a signal+background interpretation of the data (1-CL$_b$=3.7×10$^{-3}$ which is almost a 3σ effect, see table 7.2). On the other hand, when ALEPH is left out of the
combination, the results are in perfect agreement with what is expected from a background-only hypothesis (1-CL_{b}=0.49).

Interpreting the combined measurement as a lower limit on the mass of the SM Higgs boson will therefore result in a lower limit that is smaller than the one that was expected. The combined LEP results can be summarised as follows:

\[
\begin{align*}
\text{Expected:} & \quad M_H > 115.4 \text{ GeV/c}^2 \quad \text{ (at 95% CL)} \\
\text{Observed:} & \quad M_H > 114.1 \text{ GeV/c}^2 \quad \text{ (at 95% CL)}
\end{align*}
\]

At this point an important remark should be made on how (not) to interpret a lower bound on the Higgs mass. A lower bound on the Higgs mass says nothing on the probability of the Higgs mass to be higher or lower than some value. To be allowed to make such a statement the direct results must first be folded with a prior probability density distribution for the Higgs mass itself. In the next section the results from such an exercise are described.

### 7.5.4 Combining the indirect with the direct measurements

In this section the indirect measurement of the Higgs mass (see section 2.3.3) is combined with the direct exclusion limits from LEP to obtain the probability density function for the Higgs mass\(^8\).

---

\(^8\) Of course the Higgs mass (if the Higgs exists) has a single unknown value, but in the Bayesian framework the mass is treated as a stochastic variable.
Higgs production (SM Higgs decay) 114

Given the exclusion limit from the direct Higgs searches at LEP2 at 114.1 GeV/c², the additional information contained in the likelihood curve (figure 2.3) for the Higgs mass from the electroweak precision measurements below around M_H=110 GeV/c² is extremely small. Above 116 GeV/c² however, the direct searches have no sensitivity for a Higgs signal and all sensitivity to the Higgs mass comes from the indirect measurements. While the 'statistical' properties of a particle with unknown mass are ill defined, the likelihood ratios associated to these measurements can be combined in a rigorous way. The main results from such an exercise [84] and p.d.f of the Higgs mass are summarised here. In general, given a certain data set, the probability density function of the Higgs mass can be constructed using Bayes’ formula:

\[ p(M_H|\text{world data}) \propto p(\text{world data}|M_H) \cdot p(M_H) \]  

(7.12)

In this expression \( p(\text{world data}|M_H) \) describes the combined likelihood of the electroweak measurements within the SM as a function of the Higgs mass and \( p(M_H) \) is the a priori probability density function for values of the Higgs mass. They are combined to give the probability density function for the Higgs mass: \( P(M_H|\text{world data}) \).

\( p(\text{world data}|M_H) \) is a combination of the likelihood curve for the Higgs mass obtained from electroweak precision measurements and the results from the direct searches at LEP2. The exercise of [84] is based on the combined electroweak results in the summer of 2000 [85] and the direct Higgs search results at the time of the LEP fest (October 2000). To obtain the probability density function for the Higgs mass also a prior distribution for the Higgs mass, \( p(M_H) \), has to be defined. A commonly accepted choice, as is the case in the exercise whose results are discussed here, is to define \( p(M_H) \) to be flat in \( \ln(M_H) \). The information on the Higgs mass from the indirect measurements ensures a properly normalised posterior probability density function as is shown in figure 7.16.

The distribution has a sharp peak around 116 GeV/c² reflecting the excess observed in the direct searches at LEP. Some numbers characterising this distribution are:

- \( M_H = 119 \text{ GeV}/c^2 \) (median mass)  
- \( M_H < 205 \text{ GeV}/c^2 \) at 95% CL
7.6 Higgs physics in the near future

The result of the direct search for the SM Higgs boson at LEP is a hint for a signal that is however not significant enough to claim a discovery. In the next years, the discovery of the Higgs boson and the study of its properties therefore remains one of the main topics in high-energy physics.

If the Higgs boson exists and has a mass in the range as indicated by the electroweak precision measurements (roughly from 100 to 250 GeV/c$^2$) it will be discovered in the coming 5-8 years at one of the two main hadron colliders: the Tevatron at Fermilab or the Large Hadron Collider at CERN. The sensitivity of the multi-purpose experiments at the Tevatron (D0 and CDF) and LHC (ATLAS and CMS) have been investigated in terms of their discovery potential for a Higgs boson. A quick summary of the main results is presented here.

![Graphs showing Higgs mass and discovery potential](image)

Figure 7.17: The left plot shows the discovery and exclusion potential for the CDF and D0 combined SM Higgs search as a function of the Higgs mass and the collected luminosity per experiment. The right plot shows the ATLAS and CMS combined signal significance as a function of the Higgs mass for three different integrated luminosities. The 5$\sigma$ discovery mark is also indicated.

The RUN2 of the Tevatron (a proton anti-proton collider with a centre-of-mass energy of 2 TeV) has already started. The main results from the Higgs sensitivity studies [86] are summarised in the left plot of figure 7.17 where the luminosity needed (per experiment) for the Tevatron to either exclude the signal at 95% CL or to claim a discovery is given as a function of the Higgs mass. With around 10 fb$^{-1}$ of luminosity per detector (this luminosity is expected to be reached at the end of 2006 [87]), the Higgs mass can be excluded up to a mass of 180 GeV/c$^2$, but for a large range of masses many more years of data-taking are needed to claim a discovery. The Tevatron predictions were made using a simplified detector simulation and the impact of systematic uncertainties can only be estimated once real data is collected and analysed.

The big adversary of the Tevatron is the LHC collider at CERN (a proton-proton collider with a centre-of-mass energy of 14 TeV) that is scheduled to start in 2006. It will deliver about 10 fb$^{-1}$
per year (at low luminosity running) to the individual LHC detectors. In the right plot of figure 7.17 the ATLAS[88] and CMS[89] combined signal significance as a function of the Higgs mass is shown at three different values of the integrated luminosity. For masses between 200 and 500 GeV/c² the LHC sensitivity is about equal for all masses, and above that value the significance drops only very slowly. If the Higgs boson is above 140 GeV/c² it will be discovered within one year. For a light Higgs boson in the region below 125 GeV/c² it will require slightly more data. As is the case for the Tevatron predictions, the numbers assume complete and well understood detectors in addition to well understood physics backgrounds, so the actual discovery claim might take a bit longer.

From these numbers and dates it is clear that there will be an exciting race for the discovery of the Higgs boson between the various experiments and colliders in the coming decade. In the more distant future (2010+) a high luminosity linear e⁺e⁻ collider (TESLA) will allow a very precise determination of the properties of the Higgs boson like its mass, width, spin and the coupling to various quark types and gauge bosons to test the (non-)SM predictions. Although TESLA will not be constructed to discover the Higgs boson it is interesting to note that a single day of data taking would be more than enough to claim a discovery.

7.7 Summary and conclusions

In this chapter the analysis method as defined in chapter 5 has been applied to the search for the SM Higgs boson in case both the Z boson and the Higgs decay into a quark anti-quark pair. For each Higgs mass hypothesis the analysis is optimised by using (analytically where possible) the expected properties of both the ZH signal and the SM background processes. A detailed description of the method to define the sensitivity region of the analysis is given and applied to the results in the fully hadronic channel. In the year 2000 DELPHI data set no hint for an additional Higgs signal was observed and the observed lower limit on the Higgs mass was close to the one expected. The analysis can be summarised as follows:

\[
\text{Expected lower limit: } M_H > 112.0 \text{ GeV/c}^2 \quad \text{(at 95\% CL)}
\]

\[
\text{Observed lower limit: } M_H > 112.2 \text{ GeV/c}^2 \quad \text{(at 95\% CL)}
\]

The combined measurement from the four LEP experiments (using all search channels and the full LEP2 data set) resulted in a hint for a signal at a (most likely) Higgs mass of 115.6 GeV/c². The significance of the excess (2.1σ) was however not enough to claim a discovery.

After the shutdown of LEP, the search for the Higgs boson and the determination of its properties will remain one of the main topics in high-energy physics in the coming years. In particular the next 5-8 years will be very exciting at the two main hadron colliders since an important discovery is within reach. Despite the more complex detectors and analyses compared to LEP, in a sense these experiments have it more easy. With their enormous discovery (or exclusion) potential they are in a win-win situation, since an absence of the Higgs is probably even more interesting than discovering it.