Search for the Standard Model Higgs Boson at LEP

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One of the missions of the LEP program was the search for the Standard Model Higgs Boson. The skillful operation of the machine in the year 2000, the final year of operation, has allowed the four collaborations ALEPH, DELPHI, L3 and OPAL to collect 536 pb^{-1} of data at center-of-mass energies of 206 GeV or higher. This data is used to probe the existence of the Higgs boson up to a mass of around 115 GeV. Tantalizing candidates have been observed in excess over the Standard Model predictions, but without enough statistical power to claim a discovery. A Higgs boson lighter than 114.4 GeV is hence excluded at 95% confidence level.

1. Introduction

The Standard Model (SM) of electroweak interactions is one of the most successful theories: It describes the physics at the highest energy scales known today with unprecedented precision. However, the SU(2) local gauge symmetry breaking (or equivalently, the existence of massive fermions and gauge bosons) is still not understood. The *Higgs mechanism* [1] is the most widely accepted mechanism allowing for massive fundamental particles while preserving the local gauge invariance of the theory. It predicts a new scalar particle, the *Higgs boson*. Its mass is essentially unknown, theoretical considerations give an upper limit of about 800 GeV [2]. Recent fits of electroweak parameters to the data favor a light Higgs ($m_{\mathrm{H}} < 193$ GeV at 95% confidence level) [3].

2. Experimental Signatures and Event Selection

The dominant production mechanisms at LEP are the *Higgs strahlung* $\mathrm{e^+e^-} \rightarrow \mathrm{HZ}$ and the *weak boson fusion* (Fig. 1). The Higgs strahlung diagram is the dominant one up to Higgs masses of about $\sqrt{s} - m_{\mathrm{Z}}$ where the fusion diagram becomes important. The cross section as function of the Higgs mass for a center-of-mass energy of 207 GeV is shown in Fig. 2 (left).

The Higgs boson decays mainly into a pair of the heaviest particle allowed by kinematics. This is due to the fact that the couplings of particles to the Higgs are the stronger the higher their mass. Fig. 2 (right) shows the branching ratios as function of the Higgs mass. In the mass range accessible at LEP, the Higgs decays mainly into a pair of b-quarks, e.g. 74% at $m_{\mathrm{H}} = 115$ GeV.

The search analyses are inspired by the $\mathrm{HZ} \rightarrow \mathrm{b\bar{b}Z}$ final state, although the fusion diagram and the interference with the Higgs strahlung diagram and non-b decay modes are included in the efficiency calculation. The experimental signatures are determined by the Higgs and Z decay modes. In the following paragraphs, the main search channels are summarized.

2.1. Four-jet channel

The high branching ratio $\mathrm{Z} \rightarrow \mathrm{q\bar{q}}$ of about 70% makes this channel the most abundant one. The most important backgrounds are W pair production ($\sigma \sim 17$pb) where one di-jet pair happens to have a mass close to the Z mass and $\mathrm{e^+e^-} \rightarrow \mathrm{q\bar{q}}$ ($\sigma \sim 81$pb) with hard gluon radiation.

2.2. Jets + missing energy channel

Events in this channel are characterized by a missing mass close to the Z mass and two acoplanar b-jets. The major backgrounds are $\mathrm{e^+e^-} \rightarrow \mathrm{q\bar{q}e}\nu$ ($\sigma \sim 3.2$pb) where one electron escapes detection along the beam pipe and $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-} \rightarrow \mathrm{q\bar{q}}\mu\nu$ or $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-} \rightarrow \mathrm{q\bar{q}}\tau\nu$

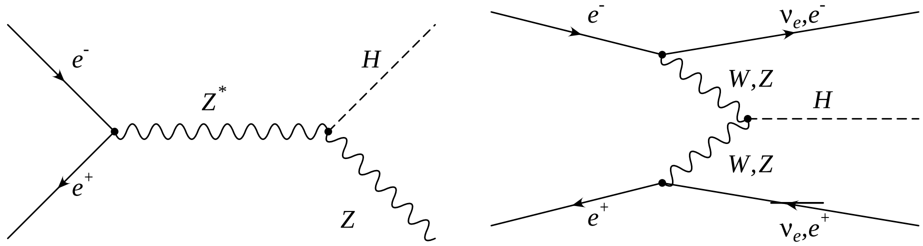

Figure 1. The dominant Higgs production mechanisms in e^+e^- collisions at LEP energies: Higgs strahlung (left) and weak boson fusion (right).

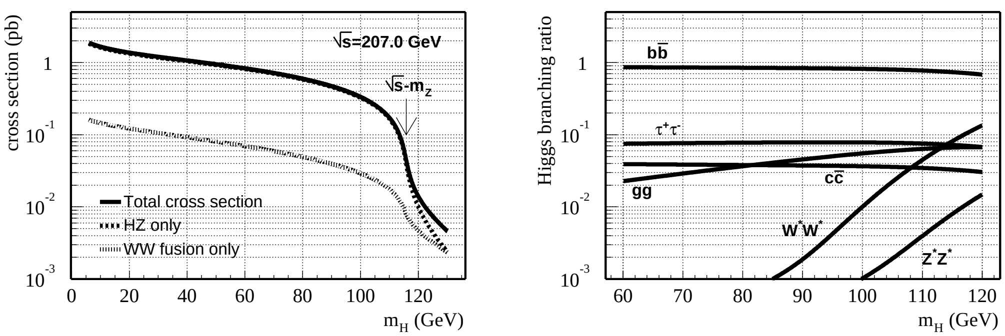

Figure 2. Higgs production cross section at LEP for a center-of-mass energy of 207 GeV as function of the Higgs mass (left). The solid line shows the total cross section, the fine dashed line the cross section of the W fusion diagram and the coarse dashed line the cross section from the Higgs strahlung process. The arrow indicates the *kinematic limit* $\sqrt{s} - m_{\mathrm{H}}$. The right plot shows the Higgs branching ratios as function of the Higgs mass. For masses reachable at LEP, the $\mathrm{b\bar{b}}$ decay mode is dominant, while $\tau^+\tau^-$ is the second most abundant. The cross sections and branching ratios were calculated using the HZHA generator [4].

events where the lepton is not identified. Pair production of Z bosons ($\sigma \sim 1.3$pb) and the process $e^+e^- \to q\bar{q}(\gamma)$ with undetected initial state radiation of photons constitute further important backgrounds.

2.3. Jets + leptons channel

Events in this channel have two leptons with a dilepton invariant mass close to the Z mass and two b-jets. The relatively low branching ratio of $Z \to \ell^+\ell^-$, 3.4% per lepton flavor, makes this a small statistics channel. However, the most important background is Z pair production (where one Z decays into quarks and the other decays into leptons) which also has a small cross section, thus making this signature extremely clean. All four experiments also include the case where the Higgs decays into a pair of τ leptons and the Z decays hadronically.

Fig. 3 shows the reconstructed Higgs mass of all LEP experiments and all search channels combined at a level of the selection where the number of expected signal events above 109 GeV is about twice the number of expected background events in the same region. Note that these mass distributions are *not* used directly to draw quantitative conclusions about the presence or absence of a signal. This is done by combining the reconstructed mass with other event properties.

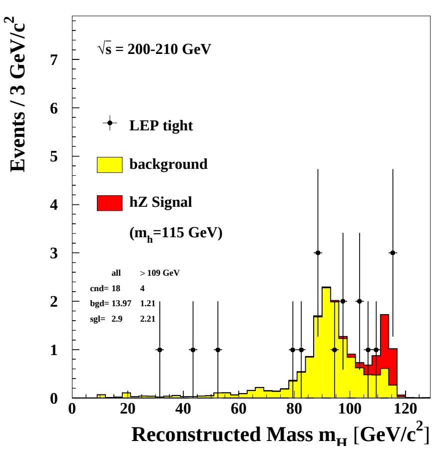

Figure 3. Higgs candidate mass ($m_{\rm H}^{\rm rec}$) distribution after tight cuts for the combination of all four LEP experiments and all search channels [5]. The light histogram represents the expected background, the dark histogram is the signal ($m_{\rm H}$= 115 GeV) on top of the background while the dots are the data. The cuts were chosen such that the ratio of the number of expected signal and background events above $m_{\rm H}^{\rm rec}$ = 109 GeV is approximately 2:1 (2.21 signal and 1.21 background events where 4 events are observed in data).

3. Statistical Method and Quantitative Results

After a more or less tight event selection, usually a *final discriminant* is constructed from several variables of which each shows some separation power between signal and background. The distribution of this final discriminant is used to calculate the following likelihood ratio Q:

$$Q(x) = \frac{\mathcal{L}(x|s+b)}{\mathcal{L}(x|b)} \qquad (1)$$

where $\mathcal{L}(x|s+b)$ is the likelihood of x under the signal+background hypothesis (similarly for $\mathcal{L}(x|b)$). If the final variable distribution is binned into a histogram, $\mathcal{L}$ is the product of the corresponding Poisson probabilities over all histogram bins. The variable x usually represents the observed data but Q can also be calculated for the expected background. Fig. 4 shows the evolution of $-2\ln Q$ as function of the Higgs mass hypothesis for the individual LEP experiments. The ALEPH result shows some excess, mainly from the four-jet channel, in the mass region around 115 GeV, which is however not observed by the other experiments. Fig. 5 shows the combination of all LEP experiments and search channels. The data are on the signal-like side of the background but are never more than 2σ away from it.

Confidence levels are calculated by comparing the data to a large number of Gedanken experiments, obtained from the expected signal and background final discriminant distributions: $\rm CL_b$ is the fraction of *background* experiments being more background like ($Q < Q_{\rm data}$) while $\rm CL_{s+b}$ is the fraction of *signal+background* experiments being more background like than the data. Values of $1-{\rm CL_b} < 5.7\cdot 10^{-7}(2.7\cdot 10^{-3})$ are interpreted as 5σ discovery (3σ evidence). Higgs masses for which ${\rm CL_s} = {\rm CL_{s+b}}/{\rm CL_b} < 0.05$ are excluded at 95% confidence level.

The evolution of $1-{\rm CL_b}$ as function of the Higgs mass hypothesis is shown in Fig. 6. The values of $1-{\rm CL_b}$ at $m_{\rm H}$= 116 GeV for the combination and the individual experiments are given in Table 1.

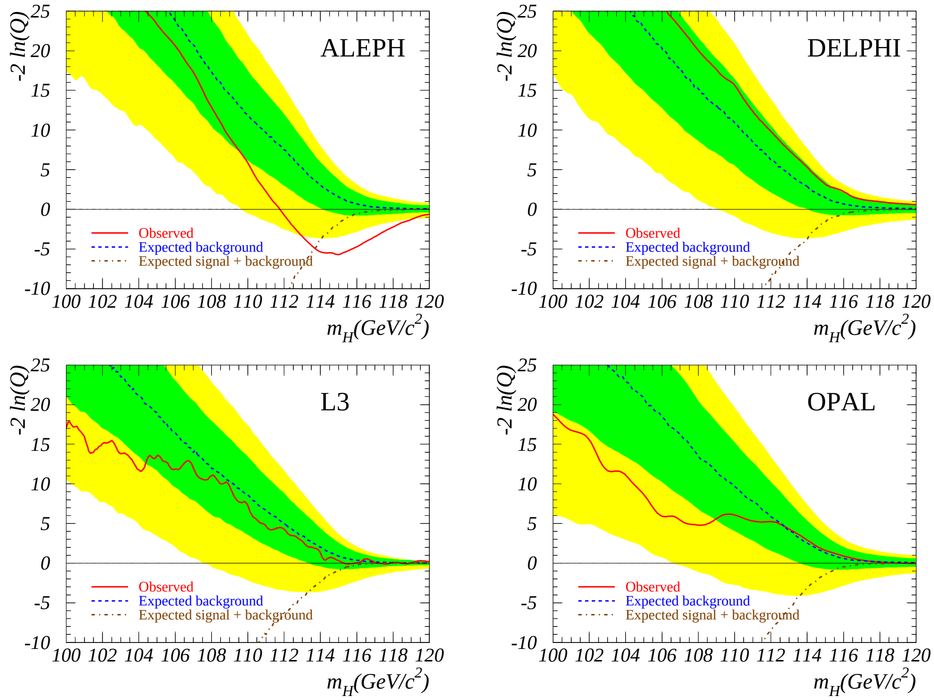

Figure 4. Evolution of $-2\ln Q$ as function of the Higgs mass hypothesis of the individual LEP experiments for all search channels combined [5]. The solid line corresponds to the observed data, the dashed line to the expected background and the dash-dotted line to the expected signal+background (for a sliding Higgs mass hypothesis). The dark and light bands indicate the 1 and 2σ deviations from the background.

4. Summary

A search for the Standard Model Higgs Boson at LEP using 2461 pb^{-1} of data (at center-of-mass energies of 189 GeV and higher) was performed. In the highest energy data sample, the ALEPH collaboration observed some highly significant candidates around a Higgs mass of 115 GeV in the four-jet channel. The probability for the background to generate such a fluctuation is 0.24%. However, the other LEP experiments do not observe any candidates with a local signal over background ratio greater than one. A lower bound on the Higgs mass is set at 114.4 GeV at 95% confidence level [5].

All the results quoted here are preliminary, however since two of the four experiments published their final analyses [6,7], one has submitted its final publication [8] and one submitted its final results to conferences [9], the final combined LEP result is expected to be similar.

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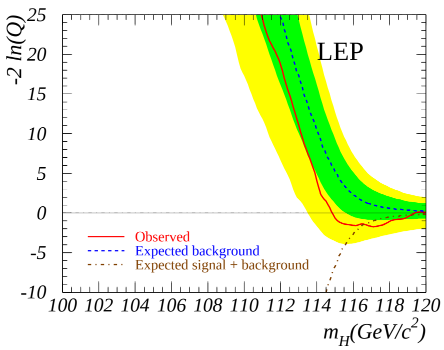

Figure 5. Evolution of $-2\ln Q$ as function of the Higgs mass hypothesis of all four LEP experiments and all search channels combined [5]. The meaning of the lines and bands is the same as in Fig. 4. The data is never more than two standard deviations away from the background over the mass range shown. The distance between the background and signal+background lines is a measure of the sensitivity (or separation power between background and signal+background) of the analysis. The observation crosses the expectation from signal+background around 116 GeV, however the separation power is very small at this mass.

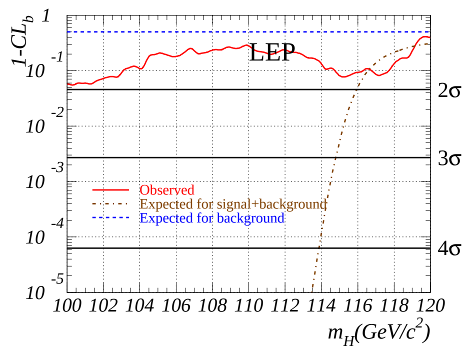

Figure 6. Probability $1 - \mathrm{CL_b}$ as function of the Higgs mass hypothesis. The solid line corresponds to the observed data, the dash-dotted line corresponds to the expectation from a signal (at each mass hypothesis) and the dashed horizontal line at $1 - \mathrm{CL_b} = 0.5$ is the expectation from background. The solid horizontal lines indicate the probabilities for a 2,3 and 4σ deviation from the background.

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	$1 - \mathrm{CL_b}$
ALEPH	0.00241
DELPHI	0.874
L3	0.348
OPAL	0.543
Four-jet	0.0570
All but four-jet	0.368
LEP	0.099

Table 1
Probability $1 - \mathrm{CL_b}$ at m_{H}= 116 GeV for the individual experiments, the LEP combined result and the four-jet and all other channels [5]. Small values indicate a deviation from the background in the signal-like direction.