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Standard Model Higgs Search at LEP–II[1]

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Abstract

The aim of the LEP experiments in their final years was to explore the highest energy collisions for a possible hint of new particles or new phenomena. Most important among the new particles is the Higgs boson. The precision electroweak data indicate that the Higgs boson could be within the reach of the LEP experiments. I summarize the experimental searches for the Standard Model Higgs boson by the four LEP experiments during the year 2000, the last year of the LEP operation. In the recently updated preliminary analyses using all the data collected in 2000, a 95% C.L. lower bound of 114.1 GeV has been obtained for the Higgs boson mass. With several significant candidate events particularly in the ALEPH data and in the 4-jet final state, the likelihood analysis shows an excess that can be interpreted as a 115.6 GeV Higgs boson. The probability for background fluctuations to produce such an excess is 3.5%.

[1]Presented at the Workshop "Physics at Linear Colliders," KEK, March 15, 2001. An updated combination of revised analyses which were not available at the time of the Workshop is also described.

1 Introduction

The Higgs boson is the last missing particle in the Standard Model (SM). Its discovery will directly prove the idea of spontaneous symmetry breaking which forms the foundation of the electroweak theory and also most of the theories beyond the SM. Its mass, though unpredictable within the SM, could shed light on physics beyond the SM. For example, a mass less than 130 GeV would imply the existence of new physics below the Planck scale. On the other hand the minimal supersymmetric extension of the SM predicts the mass of the lightest Higgs boson to be less than 135 GeV. The precision measurements of electroweak parameters prefer the Higgs mass to be less than 196 GeV at the 95% confidence level [1].

Direct searches for the Higgs boson had been carried out by the four LEP experiments for a long time and no evidence was discovered in the data collected prior to the year 2000 [2]. At the LEP Committee in September 5, 2000, however, the ALEPH collaboration reported an excess of events that suggested the production of the SM Higgs boson with mass of about 115 GeV [3], while the other three experiments did not observe any excess. One of the ALEPH Higgs candidate event is shown in Fig. 1. In fact the ALEPH excess was a bit too large for the SM Higgs boson but would be consistent if combined with the null results of the other experiments. The probability for the background to produce such an excess was estimated to be 2.5%.

It was then decided that the LEP shutdown scheduled at the end of September was postponed by one month to clarify this ambiguous situation. The LEP machine had continued its operation until November 2. The bulk of the new data were quickly analyzed and the preliminary results were presented at the LEP Committee on November 3 [4]. The significance of the ALEPH excess was slightly degraded, but the L3 collaboration observed an excess of events, especially a candidate in the missing energy final state ($\mathrm{H}\nu\bar{\nu}$), compatible with a 115 GeV SM Higgs boson [5]. Together with the "null" results of the other two experiments, DELPHI and OPAL, the overall excess at 115 GeV was estimated to be a 2.9σ deviation from the background (i.e. the background probability of 0.4%). See Table 2 below.

As it appeared that the significance of the excess had grown according to the data statistics, the LEP experiments requested for running in 2001 to determine definitely whether it is a statistical fluctuation or a discovery [4]. It was thought that, with an additional module of superconducting cavities

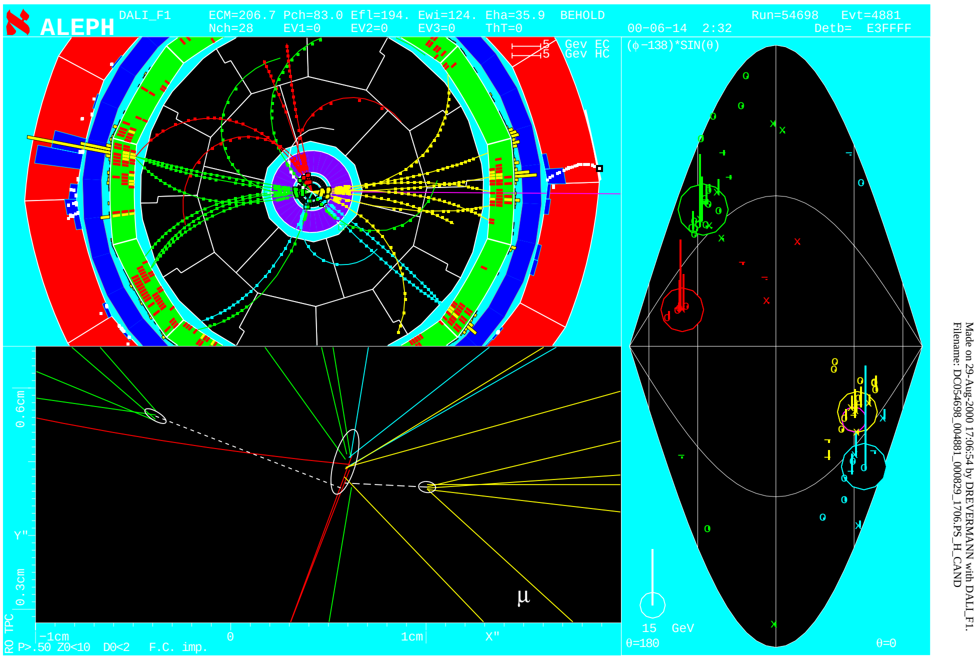

Figure 1: One of the most significant ALEPH Higgs candidate event.

available, LEP should be able to run at slightly higher energies in 2001, and therefore a four-to-six-month running would be enough to put a definite end to the controversy. On November 8, however, the CERN Management decided that the data was not sufficiently conclusive to justify running LEP in 2001, and that CERN should proceed full-speed ahead with the Large Hadron Collider project [6].

ALEPH, DELPHI, and OPAL quickly published their results updating the preliminary results presented at the LEP Committee to include all data after a thorough revision of the analysis procedures [7, 8, 9]. L3, apparently having problems with their most significant $H\nu\bar{\nu}$ candidate, finally published their result in July, 2001 [10]. The L3 publication is final. The final publications by the other three collaborations are currently in preparation.

In this note I present combined results from the four LEP experiments which are based on these recent publications [11], after describing the LEP running conditions in 2000 and the experimental analyses of the data.

2 LEP–II in the year 2000

LEP–II is the machine to pioneer the unexplored highest energy e^+e^- collisions in search of new particles and new phenomena such as the Higgs boson and the supersymmetric partners. After it left the Z^0 peak in the summer, 1995, the LEP machine started struggling for higher and higher energy while still providing reasonably high luminosity for the precision studies of the W boson.

Toward the end of 1999, the LEP machine reached the collision energy of 202 GeV, much higher than one had initially expected. During the winter shutdown in 1999–2000, the superconducting cavities were conditioned and some of the LEP–I normal copper cavities were placed back to help boost the collision energy further. To go beyond what was thought to be the maximum achievable energy, various techniques were also tried: For example, the correction magnets were used to enlarge the bending radius and the RF frequency was lowered to make the beam trajectory a bit larger so that the synchrotron radiation should be suppressed.

Because of the klystron trips, an operation at the highest energy risks the running efficiency and therefore the total integrated luminosity. To secure a high running efficiency, a new operation scheme was adopted for the running in 2000. In the new "mini ramp" scheme, the beams are first accelerated to a slightly lower energy, and, as the beam intensity decreases, they are ramped up in a few steps to the maximum energy. This scheme leaves a good safety margin in the total klystron power during each step of the operation while still providing reasonably good luminosity at the highest energies.

The LEP physics run started in April, and immediately after running at the Z^0 peak for detector calibration, LEP successfully started a stable operation at 205 GeV. Later it reached the maximum collision energy of 209 GeV. After ALEPH announced an excess of events in September, all effort was made to maximize integrated luminosity at higher energies. The total integrated luminosity taken at energies larger than 206 GeV ($= M_Z +$ 115 GeV) was 542 pb^{-1} for the four LEP experiments. Including the data in the previous year, the integrated luminosity above 189 GeV, corresponding to the data sample used in the combination in this note, was 2465 pb^{-1}.

3 Higgs Search on Threshold

At LEP energies the SM Higgs boson (H) is produced mainly in the Higgsstrahlung process, $e^+e^- \rightarrow$ HZ. Additional contributions from t-channel WW and ZZ fusion processes are still small. The cross sections for these processes are calculated with a precision better than 1% including the initial state radiation. For a mass in the vicinity of 115 GeV, the SM Higgs boson is expected to decay mainly into $b\bar{b}$ quark pairs (74%), while its decays to tau pairs, WW*, gluon pairs (approximately 7% each), and to $c\bar{c}$ quark pairs (4%) are less important. The branching ratio into $b\bar{b}$ is obtained within a 2% accuracy. Only the decays into $b\bar{b}$ and $\tau^+\tau^-$ are used in the searches for the SM Higgs boson at LEP. Higgs candidate events are selected separately for the following four different final state topologies:

- **four-jet final state:** $(H\rightarrow b\bar{b})q\bar{q}$ where the associated Z boson decays hadronically. About 50% of all Higgs production end up with this final state for mass of 115 GeV.

- **missing energy final state:** $(H\rightarrow b\bar{b})\nu\bar{\nu}$ where the Z boson decays into a neutrino pair. About 15% of Higgs production.

- **leptonic final state:** $(H\rightarrow b\bar{b})\ell^+\ell^-$ where the Z boson decays into an electron pair or a muon pair (ℓ denotes an electron or a muon). The "golden" final state with a good Higgs mass resolution and small background contamination, but only 5% of Higgs production.

- **tau lepton final state:** $(H\rightarrow b\bar{b})\tau^+\tau^-$ or $(H\rightarrow \tau^+\tau^-)q\bar{q}$. About 7% of Higgs production.

These four final states cover roughly 80% of all Higgs production. The four-jet final state has the best statistical sensitivity which is comparable to that combining the other three final states.

After kinematical selection cuts to reduce the background from two-photon processes and radiative returns to the Z boson, $e^+e^- \rightarrow Z\gamma(\gamma)$, the remaining background is mainly from $q\bar{q}$ pair production with (multiple) gluon radiation, WW, and ZZ processes. To reduce the background further, we utilize "b-tagging," i.e. the requirement of b quark in the hadronic final state, and the reconstruction of the "Higgs boson" mass, M_{rec}, which are described below.

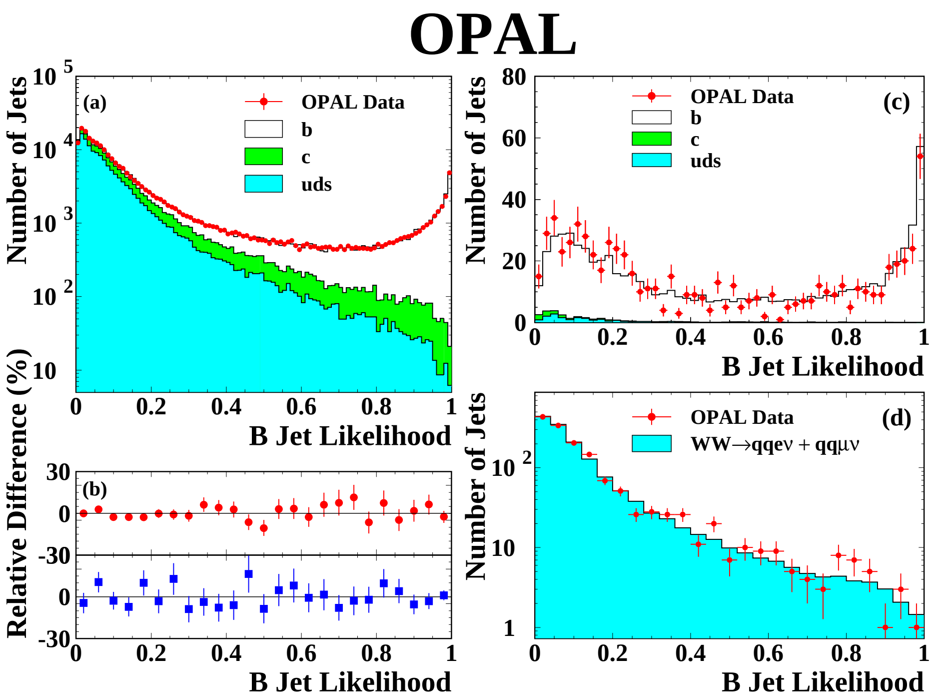

Figure 2: An example of the b-tag performance/modeling checks. (a) and (b) show the comparison between data and MC simulations. (c) B-tagging over the $b\bar{b}$ sample taken at the Z^0 peak. (d) The semi-leptonic WW sample that contain no b jet.

3.1 B-Tagging

The most important handle to identify b quarks in the hadronic final state is the long lifetime of the b hadrons. The b hadrons typically travel several mm before they decay into lighter hadrons at LEP energies. Thus, by finding these decay vertices with the help of the high resolution Si micro vertex detector, b quark production is identified with high efficiency. To distinguish c hadrons which also travel some distance before decaying, the multiplicity of the tracks coming out of the vertices, the impact parameters of these tracks, and/or the so-called "vertex mass" are utilized. To make the best of these discriminating variables, either likelihood selections or neural network algorithms are applied. Almost all background from WW are discarded this way.

The performance of the b quark tagging is carefully checked by using Z$\rightarrow$ $q\bar{q}$ taken at the Z^0 peak and WW$\rightarrow$ $\ell\nu q\bar{q}$. By applying the b-tag algorithm to one of the jets in the Z$\rightarrow$ $q\bar{q}$ events, a sample of pure b quark jets is obtained. Also WW$\rightarrow$ $\ell\nu q\bar{q}$ serves as a sample that does not contain b quarks. An example of the b-tag performance / MC modeling checks using these control samples is shown in Fig. 2.

3.2 Mass Reconstruction

Even after the powerful b-tag selection, there are much more background events, mainly from ZZ and multi-jet Z$\rightarrow$ $q\bar{q}$ events, than possible Higgs signals. Then to discriminate the signal further, the mass of the hypothetical Higgs, M_{rec}, is reconstructed from the kinematics of the event. The width of the Higgs boson is in the order of tens of MeV for the mass of interest and is negligible compared to the measurement resolutions. Therefore the Higgs signal should appear as a peak in the reconstructed mass distribution.

The kinematical mass reconstruction is tested using the WW events and its resolution and possible bias are checked. The reconstructed mass resolution is typically 2–5 GeV for each event (about 3.5 GeV if averaged over the final states and experiments).

The mass distributions obtained from the analyses using all the data are shown in Fig. 3. The three histograms correspond to different tuning of final selection cuts; In the lower histogram the expected signal to background ratio is better but with poorer statistics.

Evidently, for the Higgs boson with mass of 115 GeV, it is hard to conclude its existence or non-existence from the reconstructed mass distribution only. It is reminded that only about 10 Higgs events, depending on the final selection cuts, are expected in the final selected sample; The average collision energy of 206 GeV is barely enough for production of a 115 GeV Higgs boson.

To make the best of the LEP data and to draw some conclusion on the 115 GeV Higgs boson, we now turn to a probability analysis that uses "Higgs likelihood" of each Higgs candidate event.

3.3 Higgs Probability Analysis

Each LEP experiment utilizes a likelihood analysis or an artificial neural network to make a final selection of candidate events. The output of the

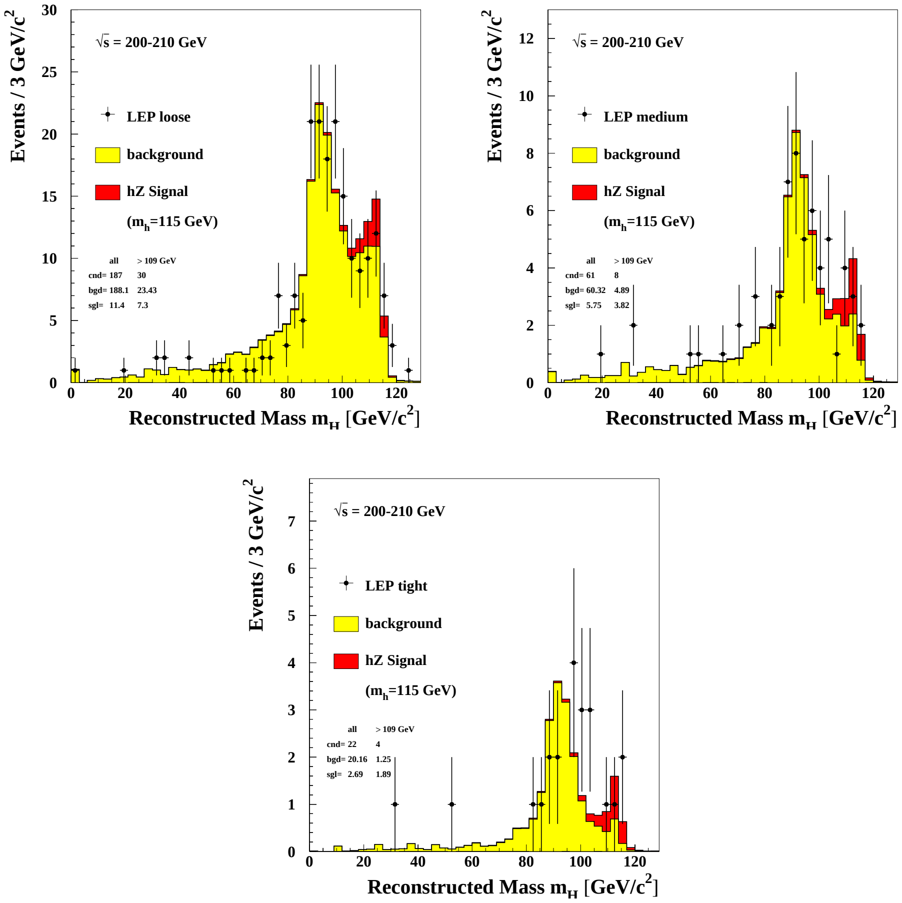

Figure 3: Distributions of the reconstructed Higgs mass for three different selections with increasing signal purity. The loose/medium/tight selections correspond to a signal to background ratio of 0.5/1.0/2.0 in the reconstructed mass region above 109 GeV.

	Expt	E_{CM}	Type	$M_{\rm rec}$	Weight
1	Aleph	206.7	4-jet	114.3	1.73
2	Aleph	206.7	4-jet	112.9	1.21
3	Aleph	206.5	4-jet	110.0	0.64
4	L3	206.4	E-miss	115.0	0.53
5	Opal	206.6	4-jet	110.7	0.53
6	Delphi	206.7	4-jet	114.3	0.49
7	Aleph	205.0	Lepton	118.1	0.47
8	Aleph	208.1	Tau	115.4	0.41
9	Aleph	206.5	4-jet	114.5	0.40
10	Opal	205.4	4-jet	112.6	0.40

Table 1: The ten most significant candidates.

likelihood analysis or the neural network, which we denote as $\mathcal{G}$, provides a good discriminating variable for each candidate event. The variable $\mathcal{G}$ serves as a "Higgs likelihood" and reflects particularly the result of the b-tagging of the event. In Table 1 properties of the 10 most significant candidate events are listed, where the last column lists "weights" of the events for $M_H = 115$ GeV[2].

In the two dimensional distributions of $\mathcal{G}$ and the reconstructed mass M_{rec} for all the selected candidate events, a binned likelihood analysis has been made. Two likelihood values are then obtained: A likelihood $\mathcal{L}_b$ that the data are all background processes, and a likelihood $\mathcal{L}_{s+b}(M_H)$ that the data are a combination of the Higgs signal and the background for a given value of Higgs mass, M_H. Then the likelihood ratio $Q \equiv \mathcal{L}_{s+b}/\mathcal{L}_b$ provides a good indicator of Higgs production. For convenience, we use the quantity $-2\ln Q$, which, in the limit of high statistics, corresponds to the χ^2 difference between the signal+background and the background-only hypotheses; It becomes negative if there is a Higgs signal.

The values of $-2\ln Q$ as a function of the assumed Higgs mass are shown in Fig. 4. For a comparison, the expected $-2\ln Q$ values for 115 GeV Higgs is also drawn as a dotted line. There is a minimum at $M_H = 115.6$ GeV, which could indicate a possible deviation from the background-only hypothesis.

[2] A weight of each event is defined in such a way that it contributes linearly to the log likelihood ratio, $-2\ln Q$, which is described below.

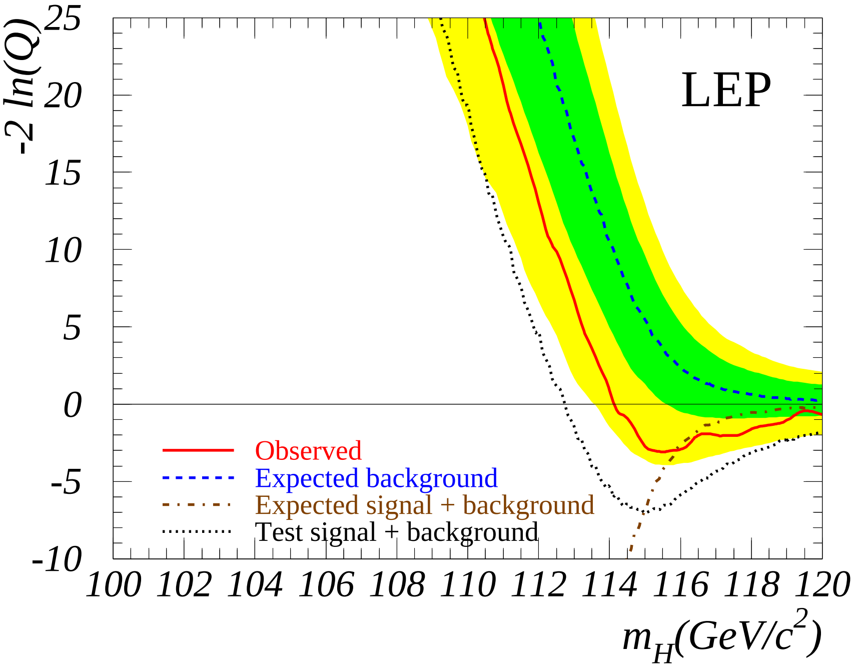

Figure 4: The observed values of $-2\ln Q$ as a function of the Higgs mass M_H (the solid line). The shaded bands are the regions within ±1 and ±2 standard deviations (for each value of M_H) for the background-only case. The dotted line indicates the behavior expected for the 115 GeV Higgs boson.

In Fig. 5 the expected distributions of $-2\ln Q$ for the assumed Higgs mass of 115.6 GeV are plotted. The separation between the distribution of the background and that of the Higgs production indicates the statistical power of the LEP data to distinguish the 115.6 GeV Higgs boson. The distributions in Fig. 5 are normalized to represent probability density distributions. The observed value is indicated by the vertical line. The "background" probability that the background fluctuates to give the value of $-2\ln Q$ equal to or lower than the observed one will give a degree of compatibility with the background hypothesis. It is given by the area of the background distribution integrated to the left of the vertical line, which is 3.5%, corresponding to a 2.1σ deviation in a "one-sided Gaussian" convention.

A few internal consistency checks have been made. In Fig. 6, the probability density distributions for the 4-jet final state and for the other final

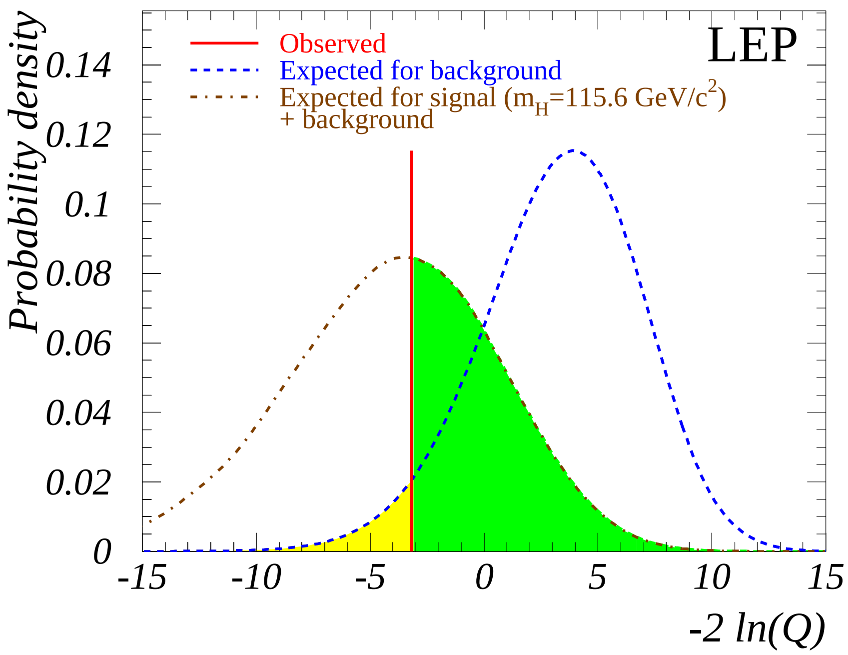

Figure 5: The probability density distributions of $-2\ln Q$ for the background (the right distribution) and for the 115.6 GeV Higgs production (left) for all data. The observed value is indicated by the vertical line. The background probability (3.5%) is the area of the background distribution integrated to the left of the vertical line.

states are compared. The two subsets of data have similar expected sensitivity. The excess concentrates mainly in the 4-jet final state. In Fig. 7, the probability density distributions for the individual experiments are separately plotted. A large difference between ALEPH and DELPHI is observed. The background probabilities of the individual experiments are listed in Table 2. It is seen that both the ALEPH and L3 excesses have decreased since November 2000 after including all data and thorough revisions of the analysis procedures. Finally the data are subdivided in high- and low-purity subsets so that the two subsets have approximately equal expected sensitivity. The contributions to $-2\ln Q$ are consistent and the low-purity subset is slightly more signal-like (negative). Hence the observed excess is not due to a few events with exceptionally high weights only.

A lower bound for the SM Higgs boson mass can be derived from these

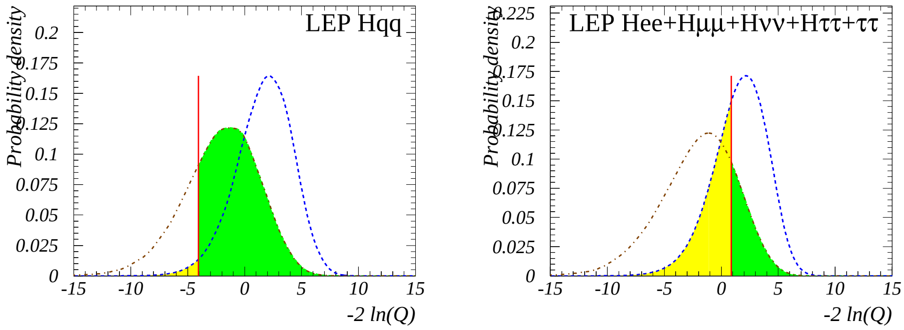

Figure 6: The probability density distributions for 4-jet final state (Hqq) and for the other final state. The vertical lines indicate the values obtained from data.

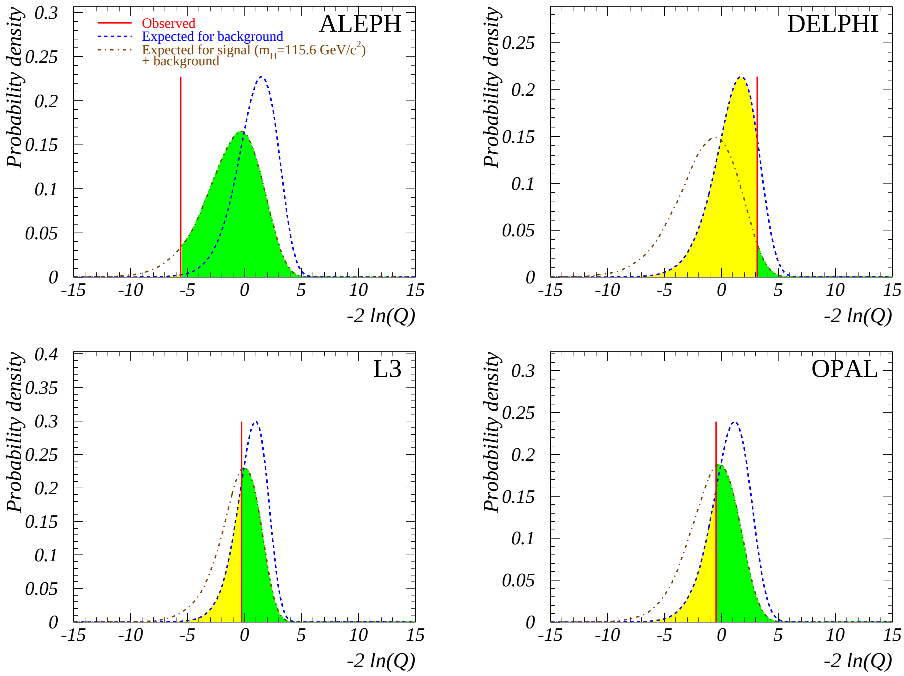

Figure 7: The probability density distributions for each of the four LEP experiments. The observed values are indicated by the vertical lines.

probability density distributions [12]. It is 114.1 GeV at the 95% confidence level while a lower bound as good as 115.4 GeV was expected from the statistics. The observed and the expected lower bounds obtained for ALEPH are 111.5 GeV and 113.8 GeV, while they are 114.8 GeV and 114.9 GeV for the other three experiments combined.

	ALEPH	DELPHI	L3	OPAL	LEP
Nov 2000	6.5×10^{-4}	0.68	0.068	0.19	4.2×10^{-3}
Published	2.6×10^{-3}	0.77	0.32	0.20	0.035

Table 2: The background probabilities presented in November 2000 and those published later in Ref. [7, 8, 9, 10]. The combined results are also shown [4, 11].

4 Conclusion

The LEP run in the year 2000 was a great success in achieving large integrated luminosity at the maximum possible energies. In the search for the Standard Model Higgs boson, there is an excess which can be interpreted as production of the Higgs boson with a preferred mass of 115.6 GeV. The probability for the background fluctuations to make such an excess is 3.5%. This excess is observed mainly in the ALEPH data and in the 4-jet final state.

Combining the data from the four LEP experiments, a new lower bound for the mass of the SM Higgs boson has been derived; It is 114.1 GeV at the 95% confidence level.

References

[1] For a most updated (preliminary) summary of the electroweak precision measurements, see the web page of the LEP Electroweak Working Group, `http://lepewwg.web.cern.ch/LEPEWWG/`.

[2] Shan Jin, "*Search for Standard Model Higgs Boson at LEP2*," Proc. ICHEP-2000, Ed. C.S. Lim and T. Yamanaka, Vol II, p.1105;

P. Igo-Kemenes, "*Searches for New Particles and New Physics: Results from e^+e^- Colliders*," ibidem, Vol I, p.133.

[3] D. Schlatter for ALEPH Collaboration, "*ALEPH Status Report*," presented at the LEP Committee Open Session, September 5, 2000.

[4] P. Igo-Kemenes for ALEPH, DELPHI, L3, OPAL, and the LEP Higgs Working Group, "*Status of Higgs Boson Searches*," presented at the LEP Committee Open Session, November 3, 2000. (The slides of the talk are available at `http://lephiggs.web.cern.ch/LEPHIGGS/talks/`.);
The LEP Higgs Working Group, "*Standard Model Higgs Boson at LEP: Results with the 2000 Data, Request for Running in 2001*," submitted to the LEP Committee and to the CERN Research Board, November 3, 2000.

[5] L3 Collaboration, M. Acciarri *et al.*, Phys. Lett. **B495** (2000) 18.

[6] CERN Press Release: "*LEP shuts down after eleven years of forefront research*," `http://press.web.cern.ch/Press/Releases00/`

[7] ALEPH Collaboration, R. Barate *et al.*, Phys. Lett. **B495** (2000) 1.

[8] DELPHI Collaboration, P. Abreu *et al.*, Phys. Lett. **B499** (2001) 23.

[9] OPAL Collaboration, G. Abbiendi *et al.*, Phys. Lett. **B499** (2001) 38.

[10] L3 Collaboration, M. Acciarri *et al.*, CERN-EP/2001-049, submitted for publication in Phys. Lett. **B**.

[11] ALEPH, DELPHI, L3 and OPAL Collaborations, and the LEP working group for Higgs boson searches, "*Search for the Standard Model Higgs Boson at LEP*," LHWG Note/2001-03, ALEPH 2001-066, DELPHI 2001-113, L3 Note 2699, OPAL Physics Note PN479, July, 2001.

[12] See Appendix A of the following reference:
ALEPH, DELPHI, L3 and OPAL Collaborations, and the LEP working group for Higgs boson searches, "*Searches for Higgs Bosons: Preliminary combined results using LEP data collected at energies up to 202 GeV*," CERN-EP/2000-055.