The Search for the Higgs Boson in the Four-Jet Channel at LEP

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The four-jet channel played an important role in the search for the Higgs boson at LEP during its second phase at centre-of-mass energies above the WW threshold, from 1996 until 2000. In an outstanding last year of running, LEP delivered a substantial integrated luminosity above 206 GeV, and first hints of a Higgs boson with mass 115 GeV/c^2 might have been observed. Unfortunately this search could not reach a definite conclusion. A review of the salient features of the analysis in the four-jet channel and the robustness of the exciting results found in this topology in 2000 is given.

1. HISTORICAL SYNOPSIS

At LEP, the Higgs boson is produced in association with a Z via the Higgsstrahlung process. At LEP1 this process, often referred to as the Björken process where the associated Z is off mass shell, allowed the searches to span a mass range up to about 65.6 GeV/c^2 [1]. At LEP2 the associated Z is produced on mass shell, which provides an additional kinematic constraint. The search range is then restricted to the hZ kinematic threshold $\sqrt{s}$-m_{Z}, unless unrealistically large integrated luminosities are accumulated.

1.1. The LEP1 Years

At LEP1, only signatures with charged leptons and neutrinos were searched for [2,3]. For a very small Higgs boson mass hypothesis, the Higgs boson is either long lived or decaying to a pair of leptons. It was thus searched for in events with two acoplanar leptons and missing energy. For intermediate mass hypotheses, low multiplicity hadronic final states and monojet topologies were investigated. For larger mass hypotheses, searches were conducted in two-jet and two-neutrino, electron or muon signatures. The background for these final states is small, in particular because of the absence of double resonant four-fermion processes. In the four-jet channel, the overwhelming background of $\mathrm{e^+e^-} \to \mathrm{q\overline{q}}$(g...) (with hard gluon FSR, this process will be referred to as QCD background) prevented this topology from being considered.

1.2. The LEP2 Years

At LEP2, at centre-of-mass energies well above the Z resonance, the QCD background is reduced by more than two orders of magnitude. The four-jet channel then becomes the predominant signature because of its large branching fraction. For comparison, its observation sensitivity is ∼2.5 GeV/c^2 above that of the second most sensitive channel at LEP2[1], the missing energy channel [2]. However, the combination of all leptonic channels (charged and neutral) is nearly as sensitive as the four-jet channel alone, and the combination of all channels is ∼ 1 GeV/c^2 more sensitive than the four-jet channel alone. The role of these channels is therefore crucial as well.

Because some of the backgrounds are largely irreducible, about eight signal events are required to be produced in each experiment for a 3σ observation. Since the cross section close to the kinematic threshold is of the order of 0.04 pb, the combined observation sensitivity can thus reach the kinematic limit when ∼200 pb^{-1} are collected by each experiment individually. Such small numbers of events illustrate how distinctly a Higgs boson signal can be seen at LEP.

1.3. Year 2000

In year 2000, with ingenious operation and outstanding performance [4], LEP delivered a sufficient amount of data at centre-of-mass ener-

[1] All experiments combined for an integrated luminosity equivalent to that collected in 2000.

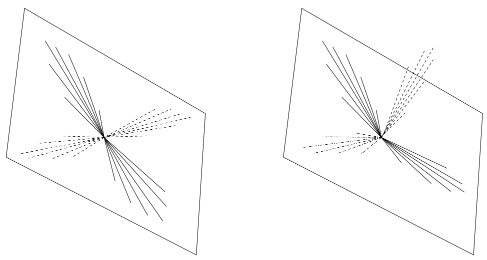

Figure 1. Four-jet event topology (left) in the signal hypothesis for a Higgs boson mass close to the kinematic threshold and (right) for the backgrounds (e.g. $e^+e^- \to ZZ$).

gies above 206 GeV (about 540pb^{-1} were actually collected by the four experiments), to allow the combined 3σ observation sensitivity to reach 115 GeV/c^2. In this last window open on Higgs boson searches at LEP, an excess of events consistent with the production of a Higgs boson with mass around 115 GeV/c^2 was indeed observed. As expected, most of the effect was observed in the four-jet channel and is discussed here. A review of the combined results is given in Ref. [3].

2. THE FOUR-JET CHANNEL

Because the Higgsstrahlung is the only signal process contributing to the four-jet channel, the final state is formed of two jet pairs, one with an invariant mass close to that of the Z and the other with the mass of the Higgs boson. In this channel, only the decays of the Higgs boson into a pair of b quarks are considered. The latter pair is therefore expected to be well b-tagged.

For a Higgs boson mass hypothesis around 115 GeV/c^2, the Z and the H are produced almost at rest, which causes the four jets to be contained in a plane (see Fig. 1). The three main background processes are $e^+e^- \to ZZ$ $\mathcal{O}(2\text{ pb})$, $e^+e^- \to W^+W^-$ $\mathcal{O}(15\text{ pb})$ and $e^+e^- \to q\overline{q}$ $\mathcal{O}(100\text{ pb})$. Only occasionally do the four fermion background processes lead to a characteristic planar topology.

In the signal final state with $Z \to b\overline{b}$ (referred to as 4b), a larger signal purity, but also more ambiguities for the jet pairing are expected compared to the case where the Z decays to a light flavor quark pair. To best profit from the specificities of these two cases, they are treated as independent channels within the four-jet analysis. The ZZ process is the largest background to the 4b sub-channel, with a small contribution from $e^+e^- \to b\overline{b}$ with FSR hard gluon splitting to a pair of b-quarks. The ZZ process is only the next-to-highest background to the 2b final state, because these events are expected to have a reconstructed Higgs boson mass close to that of the Z and not 115 GeV/c^2. The W^+W^- process, of larger cross section, contributes only through b quark mis-identification and even more rarely via CKM suppressed W decays to $b\overline{c}$ or $b\overline{u}$. The $e^+e^- \to b\overline{b}$ production process contributes only with two hard FSR gluons or an FSR gluon splitting to a pair of quarks. These events are particularly tedious because of QCD dynamics, which favours a planar configuration and therefore reconstructed masses near the kinematic threshold. Consequently, it is the largest background in the 2b channel for mass hypotheses near the kinematic threshold.

Although the analysis is largely based on the tagging of b jets and the mass reconstruction, event shape variables, although less discriminanting, are quite helpful in reaching the highest possible sensitivity.

2.1. Reconstructed Mass

At LEP2, the interpretation of the analysis results was done with a test statistic (the likelihood ratio -2lnQ) [3] built to profit from the discriminating power of variables such as the b-tagging, the reconstructed mass or the output of a neural network used to combine multiple analysis variables. The number of events observed and expected from signal and background predictions alone are therefore not sufficient to derive the result. Still, these numbers are instructive.

To equitably depict the results of all experiments, a common purity level is requested. The purity criterion used in this subsection is the expected signal-to-noise ratio at large reconstructed masses. The combined results of the searches in the four-jet channel alone, with various requirements on the purity, are displayed in Fig. 2. As shown in Table 1, the number of observed events

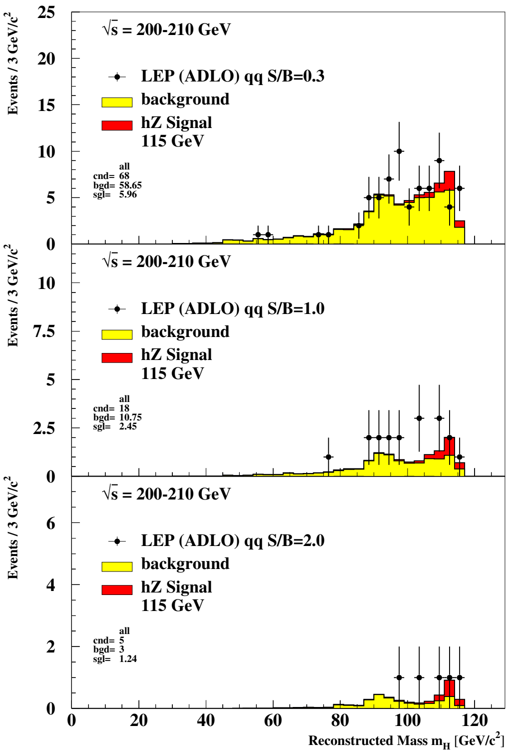

Figure 2. The distribution of the reconstructed mass for data (points with error bars), all background processes (light shaded histogram) and a 115 GeV/c^2 Higgs boson signal (shaded histogram), at different levels of purity (0.3, 1 and 2).

is more consistent with the numbers of events expected in the signal plus background hypothesis, than in the background-only hypothesis. The agreement with the signal plus background expectation is observed over the full spectrum, at large masses and at all purities.

2.2. Likelihood and Confidence Levels

This consistency is reflected in the behaviour of the combined likelihood ratio as a function of the Higgs boson mass hypothesis, as shown in Fig. 3a. A pronounced minimum clearly indicates an excess of significant four-jet events consistent with the production of a Higgs boson with mass 115 GeV/c^2. The probability that the minimum

Table 1. Number of background and 115 GeV/c^2 signal events expected and the number of candidate events at different levels of purity, for the full spectrum of reconstructed mass and for a domain enriched with signal ($\mathrm{M_{rec}} > 108$ GeV/c^2).

Purity	0.3	1	2	0.3	1	2
	Full Spectrum			$\mathrm{M_{rec}} > 108$ GeV/c^2		
Bkg.	58.7	10.8	3.0	13.1	2.4	0.7
Sig.	6.0	2.5	1.2	3.8	1.7	1.0
Data	68	18	5	19	6	3

is even more pronounced in the background only hypothesis (denoted 1-CL_b) is shown in Fig. 3b. At 115 GeV/c^2 this probability amounts to approximately 1% and corresponds to a $\sim$2.4σ deviation from the standard model expectation compatible with the $\sim$2.2σ deviation expected in presence of signal.

2.3. Consistency among experiments

The expected distributions of the likelihood ratio, obtained with a large number of gedanken experiments, and the observed value of the likelihood ratio are shown for each individual experiment in Fig. 4. The integrals of the light shaded regions in the Fig. 4 indicate compatibility with the background only prediction or 1-CL_b probability. Conversely the integrals of the dark shaded regions indicate the compatibility with the signal (also denoted CL_s). In ALEPH a large excess of events, significantly supporting the signal hypothesis, is observed [5]. Although less significant, an excess slightly favouring the signal hypothesis is observed in OPAL [9]. The results of both the DELPHI [6] and L3 [7,8] experiments are compatible with the background prediction, but are not inconsistent with the presence of signal [6]. All experiments are compatible with the signal hypothesis.

2.4. High purity candidate events

A list of the most significant events (*i.e.* with highest weight or s/b ratio, determined from expected probability densities of the aforementioned discriminant variables for a Higgs boson mass hypothesis of 115 GeV/c^2) is reported in Table 2 (the events labeled a, b, c, and d therein

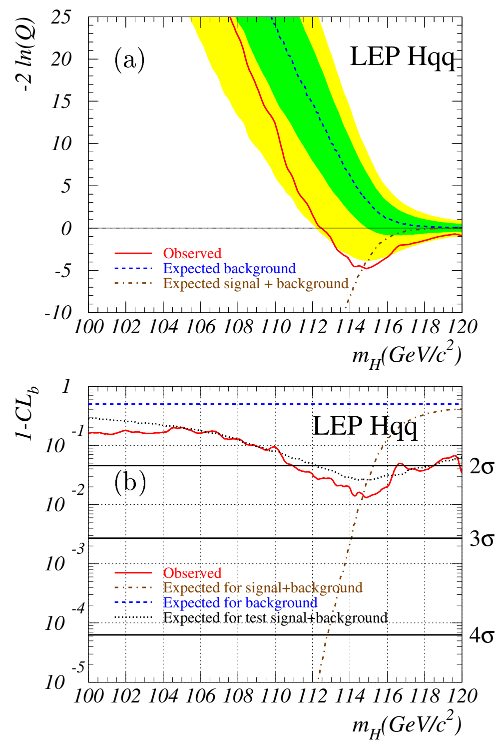

Figure 3. (a) The likelihood estimator -2lnQ and (b) 1-CL$_b$ as a function of the Higgs boson mass hypothesis. The dark and light shaded regions around the background expectation in (a) represent the one and two sigma bands respectively.

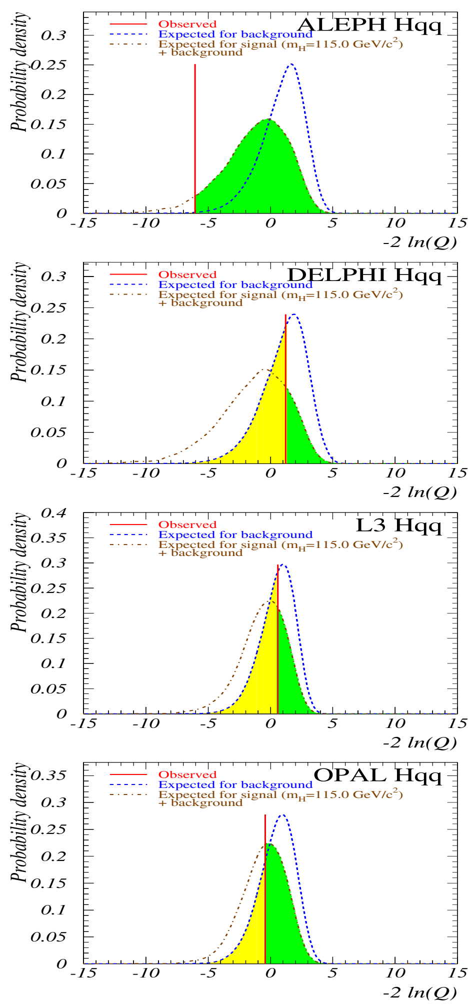

Figure 4. Estimator distributions for each individual experiment.

will be further discussed in this subsection and in setion 3). Among the eight four-jet candidate events, four are observed by ALEPH, two by OPAL and two by DELPHI. Within these limited statistics, the distribution of candidate events is compatible with being democratic. The two most significant candidate events stand out from the list and therefore deserve a closer examination.

The most significant candidate (c) is shown in Fig. 5. Beside its weight (based on b-tag, shape variables and reconstructed mass) other quantitative and qualitative aspects further show that this event well deserves its leading position in the signal ranking. For example, the jets corresponding to the pairing attributed to the Higgs boson present unambiguous displaced vertices. The 13.8 GeV/c missing momentum points precisely to the direction of the jet bearing a clearly identified muon, indicating a heavy quark semi-leptonic decay. Furthermore the muon originates from the secondary vertex. The measured invariant mass of the pair of jets with displaced vertices, with the missing momentum within the jet containing a muon taken into account, is 114.4 GeV/c^2. The energies of the the two remaining jets are 43.5 and 49.0 GeV, typical of the decay of a Z nearly at rest.

The second most significant candidate (b) is selected by the 4b sub-analysis. It has a large

Table 2. Highest purity candidate events, their reconstructed mass and their weight.

Exp.	Channel	M_{rec}(GeV/c^2)	$(s/b)_{115}$
Aleph^c	4 Jet (2b)	114.3	4.6
Aleph^b	4 Jet (4b)	112.9	2.3
Aleph^a	4 Jet (4b)	110.0	0.9
L3	$E_{\rm missing}$	115.0	0.7
Opal	4 Jet (2b)	110.7	0.7
Delphi	4 Jet (4b)	114.3	0.6
Aleph*	Electrons	118.1	0.6
Aleph	Taus	115.4	0.5
Aleph^d	4 Jet (2b)	114.5	0.5
Opal*	4 Jet (4b)	112.6	0.5
Delphi	4 Jet (2b)	97.2	0.4

* Events taken between $\sqrt{s}\sim$205 and 206 GeV.

measured visible energy of 252 GeV which can be hardly explained by a fluctuation within the visible energy resolution which is of the order of 10 GeV. In fact, a 22 GeV electromagnetic shower is observed in the forward direction. This low-angle deposit is most likely related to the beam rather than to the event, especially since the momentum imbalance is in the opposite direction. Removing it increases the reconstructed mass from 112.9 GeV/c^2 to 114.5 GeV/c^2. A fit of the most probable ZZ pairing choice is performed and yields large Z boson masses of 94.0 GeV/c^2 and 97.3 GeV/c^2. The best background explanation for this event, $e^+e^-\to$ZZ, is therefore unlikely.

The weight of the candidate event (a) is discussed in Ref. [5] and is also shown to be well justified.

2.5. Systematic uncertainties and errors

To further prove the robustness of the weight assessment it is also important to demonstrate the quality of the simulation of the pertinent variables, such as b-tagging and reconstructed mass. Numerous and comprehensive studies based on large control data samples prove that these variables are well simulated [5–9]. Moreover, if a systematic effect near the kinematic threshold had caused such an excess, similar excesses would have been seen as well in all data samples taken at centre-of-mass energies below 206 GeV (which represent altogether three times the integrated luminosity collected above 206 GeV). Such excesses are not observed.

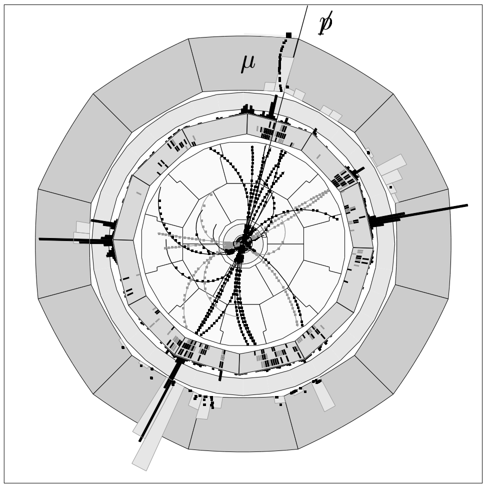

Figure 5. Event display of the most significant event. The identified muon and the missing momentum direction are also indicated.

3. ALEPH HIGHLIGHT: AN ALTERNATIVE ANALYSIS

The results reported so far for the ALEPH experiment were obtained with an analysis based on neural networks and two discriminating variables. To further substantiate this result, ALEPH has also performed an analysis based on sequential cuts in which the event weight is determined from the reconstructed mass only [5]. Both analysis streams yield very similar combined results, although the weight of each individual candidate event is different, mostly because of the use of a single discriminating variable. The event weight evolution as a function of the Higgs boson mass hypothesis is shown in Fig. 6. In the approach with sequential cuts, all the ALEPH candidate events appearing in Table 2 (a, b, c, and d) are selected as well. One additional candidate event (e) is also selected. This confirmation further shows that the ALEPH result is indeed robust.

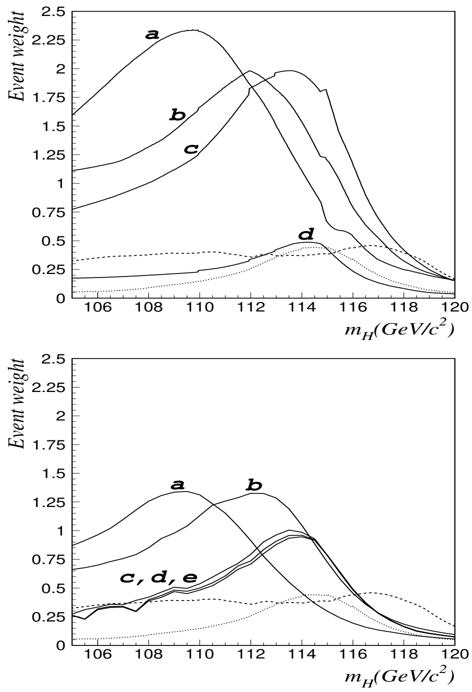

Figure 6. Candidate's individual weight evolution as a function of the Higgs boson mass hypothesis for the neural network (up) and the cut (down) stream analyses.

4. CONCLUSION

The successful operation of the LEP collider has allowed the searches for the Higgs boson to reach unprecedented high sensitivities. At the end of year 2000, these searches culminated with a tantalizing hint of the existence of a Higgs boson with mass 115.6 GeV/c^2 [3]. This hint is largely suggested by an excess of events with an extraordinary high significance. Most of these events are, as expected, selected in the four jet channel and their weights are shown to be well justified. Unfortunatelly, and despite the robustness of this search, a definite conclusion could not be reached and this first exciting hint is handed over to ongoing or future experiments at hadron colliders to be further unraveled.

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