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OBSERVATION OF AN EXCESS IN THE ALEPH SEARCH FOR THE STANDARD MODEL HIGGS BOSON

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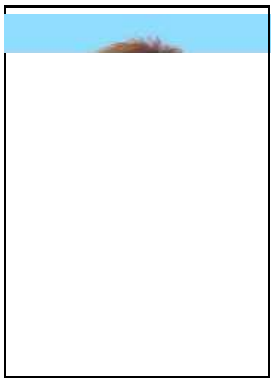

The ALEPH search for the Standard Model Higgs boson in the year 2000 revealed an excess of signal-like events, consistent with a signal hypothesis $m_{\mathrm{h}} \approx 115$ GeV/c^2. Here we present the first results after the analysis of all of the data collected during the year 2000, at collision energies up to 209 GeV, and which were published in November 2000.

1 Introduction

During the year 2000, the LEP collider was pushed to the edge of its performance envelope in order to maximize the Higgs boson[1] discovery potential[2]. The ALEPH experiment collected 216.1 pb^{-1} of data, at collision energies ranging between 202-209 GeV.

At LEP2, the Higgsstrahlung process, $\mathrm{e^+e^-} \rightarrow \mathrm{hZ}$, is the dominant mode for producing the Standard Model (SM) Higgs boson. There are also smaller contributions from the W- and Z-fusion processes to the channels $\mathrm{e^+e^-} \rightarrow \mathrm{h}\nu_e\bar{\nu}_e$ and $\mathrm{he^+e^-}$, respectively.

Figure 1(a) shows the number of Higgs events expected to be produced in the data that ALEPH collected, as a function of the Higgs boson mass. For an hypothetical Higgs boson mass of 114 (115) GeV/c^2 14.4 (10.0) events are expected. The dominant Higgs decay mode for such a signal is $\mathrm{h} \rightarrow \mathrm{b\bar{b}}$ (74%) followed by $\mathrm{h} \rightarrow \tau^+\tau^-$ (7.4%) [a]. Depending on the combination of the decay of the Higgs and of the associated Z boson, the signal events fall into one of four topologies. These are the so-called four-jet, missing energy, leptonic and tau-lepton final states, and are described in Figures 1(b)-(e).

[a] For $m_{\mathrm{h}} \sim 115$ GeV/c^2, the branching fractions to $\mathrm{h} \rightarrow \mathrm{W^+W^-}, gg$ become comparable to $\mathrm{h} \rightarrow \tau^+\tau^-$, but are not searched for explicitly in the ALEPH SM Higgs analysis.

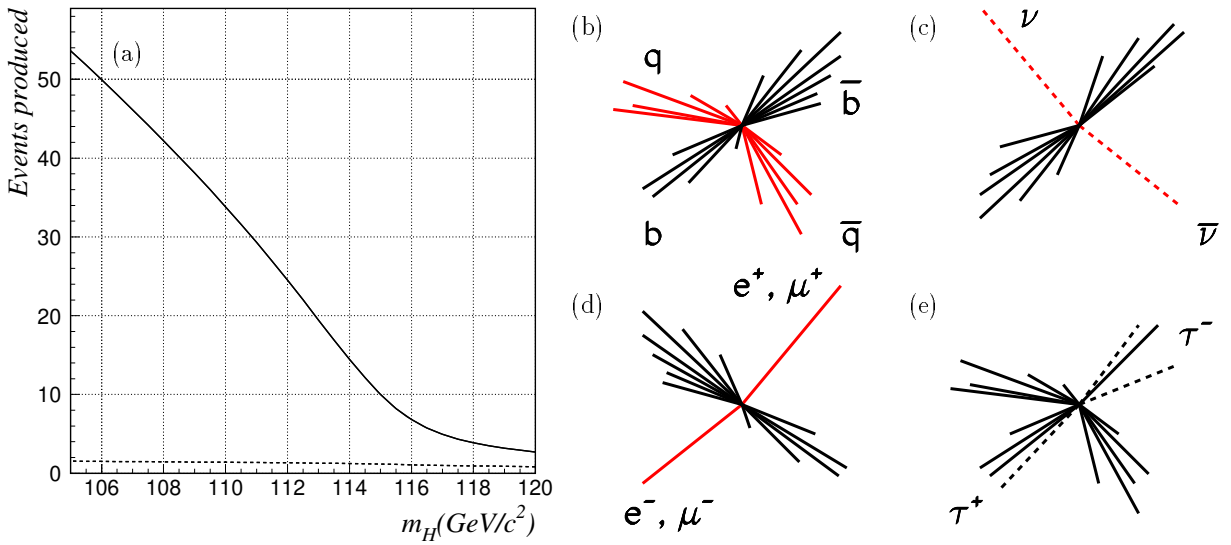

Figure 1: (a) The expected number of SM Higgs signal events produced in the year 2000 data as a function of the Higgs boson mass (solid curve). The dashed curve is the contribution from the gauge boson fusion processes, including their interference with the Higgsstrahlung process. The four main signal event topologies: (b) four-jets ($hZ \to b\bar{b}q\bar{q}$), (c) missing energy ($hZ \to b\bar{b}\nu\bar{\nu}$), (d) leptonic ($hZ \to h\ell^+\ell^-$ with ℓ =e or μ) and (e) the final states with τ leptons, $\tau^+\tau^-q\bar{q}$, when either the h or the Z decay into a $\tau^+\tau^-$ pair.

2 Higgs search strategy

At LEP2 the ALEPH Higgs search strategy rested on two alternative analysis "streams". While one of the analysis streams relies mostly on artificial neural networks (NN) for the event selections, the other stream relies mostly on more straight-forward cuts-based event selections. The motivation behind this strategy was to provide mutually cross-checked results. As the two streams have similar performance an eventual signal discovery would have to be confirmed in both.

The two streams differ in the treatment of the two most powerful search topologies: four-jets and missing energy. The treatment of the $h\ell^+\ell^-$ and $\tau^+\tau^-q\bar{q}$ channels is in all respects identical between the two streams. Table 1 shows the defining details of the cuts-stream and the NN-stream.

Table 1: The two analysis streams: "cuts" and "NN" denote the type of event selection used for the given search channel. The observables X indicate the discriminant variables used for the calculation of the confidence levels (Section 3). The $h\ell^+\ell^-$ and $\tau^+\tau^-q\bar{q}$ analyses are treated in exactly the same way in the two streams.

	cuts-stream	NN-stream
$hq\bar{q}$	cuts; $X = m_{\rm rec}$	NN; $\vec{X} = (m_{\rm rec}, {\rm NN}_{\rm output})$
$h\nu\bar{\nu}$	cuts; $X = m_{\rm rec}$	NN; $\vec{X} = (m_{\rm rec}, {\rm NN}_{\rm output})$
$h\ell^+\ell^-$	cuts; $\vec{X} = (m_{\rm rec}, b\tau\text{-tag})$	
$\tau^+\tau^-q\bar{q}$	NN; $X = m_{\rm rec}$	

The actual event selection criteria[3] for the different search channels which were used for the analysis of the 2000 data are very similar to those used for the 1999 analysis[4]. In particular, the searches used for the four-jet and tau-lepton final states in 2000 were exactly the same as in 1999. The searches in the missing energy and leptonic final states were modified slightly[3]. Furthermore, the analysis of the data was blind, as the event selection criteria were fixed before the start of the data-taking period.

3 Search results

Applying the event selections to the 2000 data results in 134 (95) events being selected in the NN-stream (cuts-stream) while 128.7 (87.6) are expected from the background. Table 2 shows how the events are distributed between the four search channels.

After the event selection stage, the likelihood of a signal in the data is quantified by means of an extended likelihood ratio, incorporating information about the numbers of events for both the background-

Table 2: The number of signal (s) and background (b) events expected, and the number of candidate events (n_{obs}) observed in the year 2000 data. For each channel the systematic error on the background is indicated. The expected background is divided into ZZ (including $\mathrm{Ze^+e^-}$ and $\mathrm{Z}\nu\bar{\nu}$), WW (including $\mathrm{We}\nu$), and $\mathrm{f\bar{f}}$ (including $\gamma\gamma \to \mathrm{f\bar{f}}$). The expectation for the signal its significance (Section 3) is computed for a Higgs boson with a mass of 114 GeV/c^2. The numbers from the $\mathrm{h}\ell^+\ell^-$ and $\tau^+\tau^-\mathrm{q\bar{q}}$ analyses are included in both the NN- and cuts-stream totals.

Analysis	Signal Events	Background Events Expected				Events Obs.
	Expected, s	ZZ	WW	$\mathrm{f\bar{f}}$	Total, b	n_{obs}
$\mathrm{hq\bar{q}}$ (NN)	4.5	23.0±1.0	8.6±0.6	15.3±1.7	46.9±2.1	52
$\mathrm{hq\bar{q}}$ (cuts)	2.9	12.6±0.7	3.2±0.2	7.9±0.7	23.7±1.0	31
$\mathrm{h}\nu\bar{\nu}$ (NN)	1.4	13.5±0.7	22.0±1.1	2.0±0.4	37.5±1.4	38
$\mathrm{h}\nu\bar{\nu}$ (cuts)	1.3	9.9±1.1	8.8±1.7	1.0±0.3	19.7±2.0	20
$\mathrm{h}\ell^+\ell^-$	0.7	26.4±0.3	2.4±0.1	1.8±0.3	30.6±0.4	29
$\tau^+\tau^-\mathrm{q\bar{q}}$	0.4	6.4±0.3	6.2±0.3	1.0±0.3	13.6±0.5	15
NN-stream total	7.0	69.3±1.3	39.2±1.3	20.1±1.8	128.7±2.6	134
Cuts-stream total	5.3	55.3±1.4	20.6±1.7	11.7±0.9	87.6±2.4	95

only and the signal+background hypotheses:

$$Q = \frac{L_{s+b}}{L_b} = \frac{e^{-(s+b)}}{e^{-b}} \prod_{i=1}^{n_{obs}} \frac{s f_s(\vec{X}_i) + b f_b(\vec{X}_i)}{b f_b(\vec{X}_i)}$$

Through f_s and f_b, the likelihood ratio Q also contains information that allows additional discrimination between the two hypotheses. f_s and f_b, respectively the signal and background probability density functions, are evaluated for each observed candidate i, with measured discriminant properties $\vec{X}_i$.

Here, the two analysis streams differ again in the treatment of the four-jet and the missing energy searches, in that the cuts-based stream uses only the reconstructed Higgs mass as discriminant, whereas the NN-based stream uses slightly more powerful two-dimensional discriminants (see Table 1). Note that –in order to keep the selection efficiency high– the $\mathrm{h}\ell^+\ell^-$ event selection is flavour independent, and that the b/τ flavour of the Higgs candidate jets is only taken into account by means of the second discriminant. For this reason, the ALEPH $\mathrm{h}\ell^+\ell^-$ search for an SM Higgs signal has to retain the second discriminant, even in the "single-discriminant" cuts-stream.

The likelihood ratio depends on the mass, m_{h}, of the signal hypothesis being tested. Figure 2(a) shows the value of $-2\ln Q$ for the NN-stream, as a function of m_{h}. The minimum of this curve indicates a high likelihood for the signal hypothesis $m_{\mathrm{h}} \approx 115$ GeV/c^2. At this mass, the likelihood of the signal+background hypothesis is ~ 34 times larger than the background-only likelihood.

As can be seen from inspecting the grey bands around the background-only expectation curve (Figure 2(a)), it is not impossible (but rather unlikely) that the observed result at $m_{\mathrm{h}} \approx 115$ GeV/c^2 could be due to a (large) fluctuation of the background. In order to quantify the probability of such a fluctuation, the fraction of background-only Gedanken experiments that are at least as signal-like as observed is calculated. This fraction, $1 - c_b$ (where c_b is the confidence level on the background-only hypothesis), is shown in Figure 2(b). For the background only scenario $1 - c_b$ has a median value of 0.5, whereas if the data contains a signal $1 - c_b$ is expected to have a localized dip to lower values. The minimum of the curve, at 1.5×10^{-3} probability, corresponds to a 3.0σ excess over the expected background.

4 Discussion and Cross-checks

The results presented here have been extensively cross-checked, with a view to find any possible systematic effects that could significantly affect the main conclusions of the searches. These checks are summarily described here. The reader is referred to the publication[3] for more details.

The differences between the cuts-stream and the NN-stream can be summarized as:

- In the cuts-stream (NN-stream) 3 out of the 4 event selections are based on cuts (neural networks);
- In the cuts-stream 3 out of the 4 discriminants are one-dimensional (m_{rec}) whereas in the NN-stream 3 out of the 4 discriminants are two-dimensional (an additional discriminant is used in addition to m_{rec}).

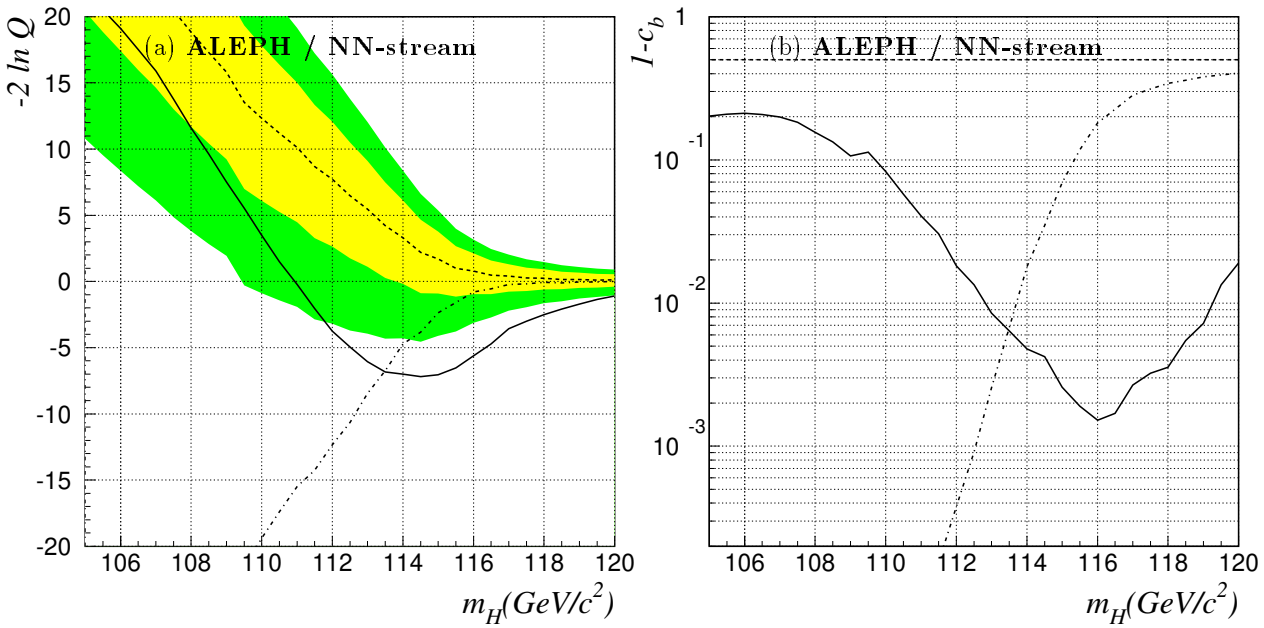

Figure 2: (a) The log-likelihood estimator $-2\ln\,Q$ as a function of the mass of the Higgs boson ($m_{\rm h}$) for the observation (solid) and background-only expectation (dashed). The light and dark gray bands around the background-only expectation are the one and two sigma regions, respectively. The dot-dashed curve shows the expected position of the median of the log-likelihood estimator when the latter is calculated at a mass $m_{\rm h}$ and includes a signal at that same mass. (b) The observed (solid) and expected (dashed) CL curves for the background hypothesis as a function of the Higgs boson mass. The dot-dashed curve indicates the location of the median CL for a Higgs signal of mass $m_{\rm h}$.

Table 3 compares likelihood ratio and significance values between the two streams. It can be readily seen that the results from the two analysis streams are in agreement. (The complete curves for the cuts-stream can be found elsewhere[3].) For the cuts-stream $1-c_b$ has a minimum of 1.1×10^{-3}, corresponding to a 3.1σ excess with respect to the expected background.

Table 3: Comparison of the main findings in the cuts-stream and the NN-stream. The Higgs boson masses are indicated in GeV/c^2. The most significant candidates in each stream are indicated (see Table 4 for details). (The LEP Higgs working group uses a different convention to compute these significances. Using that double-sided Gaussian convention, the significances quoted here would be increased by $\approx 0.2\sigma$.)

	$-2\ln\,Q$ ($m_{\rm h}$=115)	significance ($m_{\rm h}$=115)	maximum significance	significant candidates
cuts-stream	-5.7	2.9σ	3.1σ	b, c, d, e
NN-stream	-7.0	2.8σ	3.0σ	a, b, c

Most of the observed effect originates in the four-jet channel: two $\rm b\bar{b}b\bar{b}$ events (a, b) and three $\rm b\bar{b}q\bar{q}$ events (c, d, e). Table 4 gives details of these events.

The similarity of the findings in the two streams, in itself dispels any concerns about the results being a construct of the NN selection or of the more sophisticated two-dimensional discriminant. The comparison of the two streams does not however allow any inferences regarding common points between the four-jet analyses, such as the reconstructed mass discriminant and (to some extent) the choice of the pairing.

In the four-jet channel (E, p) conservation is imposed by means of a 4C-kinematic fit. The reconstructed mass $m_{\rm rec} = m_{12} + m_{34} - m_Z$ is calculated using the fitted masses for the Z and Higgs candidate dijets in the event, m_{12} and m_{34} respectively. No evidence of a bias towards the hZ threshold ($\sim \sqrt{s} - m_Z$) has been found either in the 1999 data ($\sqrt{s}$ =192 - 202 GeV) or in the 2000 data with $\sqrt{s}$ <206 GeV. In addition, the reliability of the mass reconstruction was confirmed by applying it to a large control sample of four-jet WW events selected with the cuts analysis, which had been slightly modified to include an anti-b-tagging cut.

The choice of pairing in the selected four-jet events (i.e., choosing which of the dijets corresponds to the Higgs candidate and which to the Z candidate) can obviously affect the reconstructed mass spectra.

Table 4: Details of the five four-jet candidates selected with an event weight $\ln(1+\frac{sf_s}{bf_b})$ greater than 0.5 at a Higgs boson mass of 115 GeV/c^2 in either the NN or cut streams. The jet b-tag values vary from 0 (non-b-like) to 1 (b-like). The four-jet NN output approaches 0 (1) for background-like (signal-like) events.

Candidate (Run/Event)	$\sqrt{s}$ (GeV)	$m_{\rm rec}$ (GeV/c^2)	b-tagging				4-jet NN
			jet 1	jet 2	jet 3	jet 4	
a (56698/7455)	206.5	110.0	0.999	0.836	0.999	0.214	0.999
b (56065/3253)	206.7	112.9	0.994	0.776	0.993	0.999	0.997
c (54698/4881)	206.7	114.3	0.136	0.012	0.999	0.999	0.996
d (56366/0955)	206.5	114.5	0.238	0.052	0.998	0.948	0.935
e (55982/6125)	206.7	114.6	0.088	0.293	0.895	0.998	0.820

Using the cuts analysis, it has been shown[5] that the decay angles of the h and Z candidate dijets can be successfully used to select the best pairing and thus improve discrimination with respect to the background. The decay angles are especially useful in the case of $b\bar{b}b\bar{b}$ events, where the b-tagging information is of no value for the pairing choice. The decay angles were therefore also incorporated in the four-jet NN [b]. The choice of pairing using the decay angles is well modelled in the simulation and has been used for the large data samples collected at $\sqrt{s} = 192-202$ GeV (and, for the cuts-analysis, at $\sqrt{s} = 189$ GeV as well) without any evidence of a bias.

For additional systematic checks the reader is referred elsewhere[3].

5 Conclusion

The ALEPH search for the SM Higgs boson resulted in the observation of an excess of signal-like events in collisions with $\sqrt{s} > 206$ GeV, consistent with the $m_{\rm h} \approx 115\,{\rm GeV/c^2}$ signal hypothesis. This excess, with *ca.* 3.0σ significance, has been observed in the two ALEPH alternative searches: the cuts-stream and the NN-stream. A final publication, including more detailed systematic studies, is in preparation.

The other LEP collaborations have also published their search results[6]. DELPHI and OPAL have presented their results at this conference[7]. The combined result of the SM Higgs boson search at LEP has also been presented here[8].

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[b] For events selected by the NN, the chosen pairing is that with the largest NN output. In practice this means that the NN pairing choice is essentially based on the values of m_{12}, the jet b-tags and the decay angles.