Search for the Higgs in 2 jet modes at LEP

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In the search for the Higgs at LEP, the decay modes involving 2 jets have been essential. At LEP 2 they have approximately equal significance for the four jet channel. The results obtained in 2000 are described, and a limit of $M_H > 114.2 GeV/c^2$ from this channel, or $M_H > 114.1 GeV/c^2$ in combination is obtained.

1. Introduction

The search for the Higgs was always one of the major physics aims of the LEP programme. This is because the Higgs couples to mass, and the production of large quantities of Z's was the first time that a clear signal could be distinguished for a large range of masses. The achievement is a vast improvement on previous knowledge, and the two jet modes have played a vital role.

The Higgs search at LEP[1] normally involves a signature of an H and a Z boson, which may or may not be on shell. The most likely final state, at least for high masses, is where both of these bosons decay hadronically. This is described elsewhere[2]. There are however several modes where the Higgs, or more likely the Z, decays to leptons, and these are considered here. The case where there are no jets is sufficiently rare that it has not been used at LEP 2.

2. LEP 1 searches

The most important Higgs production mechanism for LEP 1 was radiation from the primary Z, leaving an off-shell Z. Thus two bosons were expected in the event, each with an unknown mass. The search had many different decay modes to cover, dependent upon the Higgs mass. These range from quasi-stable (missing energy) through $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$, $\pi\pi$, $\tau^+\tau^-$ and $b\bar{b}$. The accompanying off-shell Z, was analyzed in l^+l^- or $\nu\overline{\nu}$ decay in order to avoid the difficulties of the hadronic environment. Thus all the LEP 1 results on the Standard Model Higgs have at most two jets.

An upper limit of 65 GeV/c^2 was placed, but, more importantly, there was a lower limit of 0. This has meant that in future there is no need to consider this difficult region.

*Thanks to PPARC who supported this work.

3. LEP 2 results

The LEP Higgs search at LEP 2 was characterized by a gradually increasing lower limit from the direct search, accompanied by a rapidly decreasing upper limit in the standard model fits. This reduced from 1000 GeV/c^2 in 1995 to 190 GeV in 2000. This, combined with the upper limits on the lightest Higgs in the MSSM, made the likelihood of a discovery seem higher. The following discussion concentrates on the kinematic limit, 115 GeV/c^2.

This trend was re-inforced by the gradually rising LEP energy and luminosity, shown in table 1.

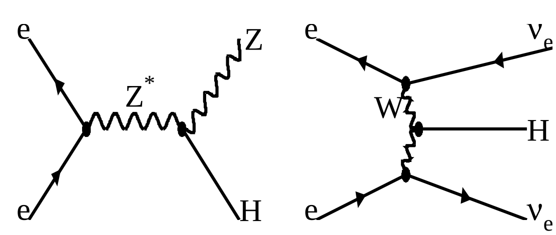

Figure 1. Higgs production through Higgstrahlung (left) or boson fusion (right).

Table 1
The luminosity profile for LEP 2, pb^{-1}.

Year	'96		'97	'98	'99				2000			
$\sqrt{s}$	161	172	183	189	192	196	200	202	204	205	207	208
$Luminosity/epxt$	10	10	60	170	30	80	80	40	10	70	130	10

The major Higgs production processes at LEP are shown in figure 1. The Higstrahlung diagram dominates when on shell Z production is kinematically allowed, but for higher Higgs masses the fusion diagram becomes important. The reason is that the fusion process does not involve a second on-shell boson, and so has no kinematic threshold.

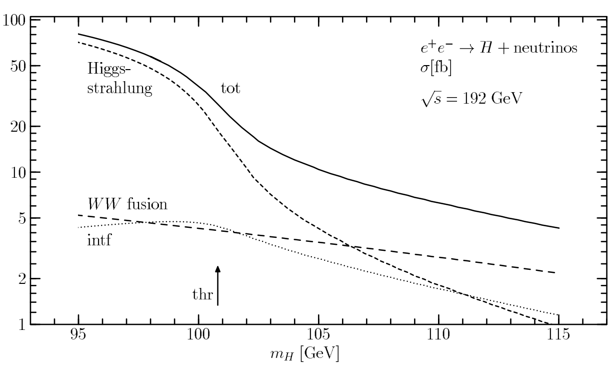

Figure 2. Total Higgs plus neutrino cross-section as a function of Higgs mass.

The cross-sections for producing a Higgs with two neutrinos from the two processes are compared in figure 2, where they are shown as a function of Higgs mass for $\sqrt{s} = 192 GeV/c^2$. It was argued in the 1990's that the fusion process might be a discovery mode for a high mass Higgs, but the total cross-section has not been adequate. For example, if the entire LEP 2 luminosity for the 4 experiments (around 2.8 fb^{-1}) had been collected at 192 GeV/c^2 11 events would have been produced. It turns out that the LEP experiments require an expectation of around 17 events *accepted* within their cuts, which have typically a 50% efficiency, in order to set an exclusion limit at 95%. In other words LEP would have had to deliver about 3 times the luminosity at 192 as was actually delivered from 161 to 208, and so the kinematic limit remains a practical upper limit on Higgs studies.

However, the presence of the fusion channel and interference do mean that the importance of the $H\nu\overline{\nu}$ channel rises with respect to the others for Higgs masses very close to the kinematic limit.

3.1. Decay channels

The decays of the Z^0 are well known from LEP studies, and need not be described here. The assumption made in the search for the Standard Model Higgs is that the decays are equally well known, if only the mass can be fixed. Figure 3 and table 2 show the decay branching fractions as a function of Higgs mass in the region of the limit set by LEP.

Table 2
Higgs branching ratios at $M_H = 115GeV/c^2$.

Decay mode	Branching ratio
$b\overline{b}$	73.6%
$\tau^+\tau^-$	7.2 %
gluons	6.6%
WW	8.1%

Table 3 shows the decay mode combinations used at LEP. There are several channels which are not covered, such as the WW or gluonic Higgs decay modes, but 81% of the decays are, and these are the ones with the most distinctive experimental signatures. However, work is progressing the WW decay modes, and it may be possible to include this at some point.

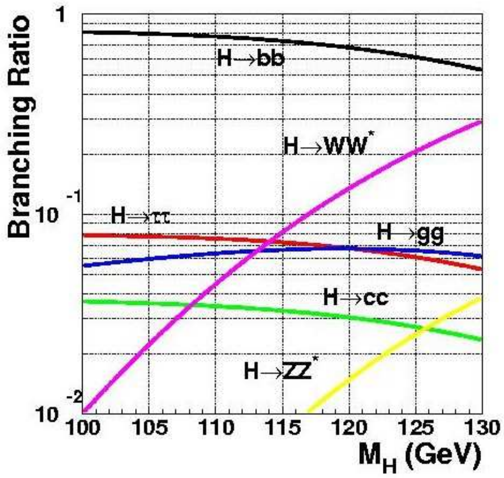

Figure 3. Higgs decay branching ratios.

Table 3
The decay modes used for the SM Higgs at LEP. The first, four-jets, is not discussed here.

Higgs	Z	Fraction
$b\bar{b}$	$q\bar{q}$	51.1%
$b\bar{b}$	$\nu\bar{\nu}$	14.7%
Any	$l\bar{l}$	6.7%
$b\bar{b}$	$\tau^+\tau^-$	2.5%
$\tau^+\tau^-$	$q\bar{q}$	5.0%

In every channel a kinematic fit is done imposing conservation of energy and momentum, and in most cases the Z mass is also constrained to the beam energy. There are thus 4 or 5 constraints, but most of the channels having missing neutrinos.

A crucial tool in looking for these events is b tagging. Each experiment monitors this very carefully by looking at, for example, semi-leptonic WW events to obtain a b quark depleted sample, and Z decays for a high statistics check on quality.

It is also vital to check the ZZ background, because if the Z decay modes are correct the events are kinematically identical. It is both a check that a signal could be seen, and an important background to control. Only the mass provides a useful separation. This is discussed in [4].

3.2. Hll Channel

Only a small fraction of Higgs will appear in this final state, but on the other hand the signature is excellent, giving a good measurement of both the Z and the Higgs without having missing energy. This means that the mass resolution is rather good, and unlike the four jet mode there are no difficulties assigning partons to bosons, so the tails of the distribution are very clean.

The experimental selection is relatively easy, and experiments tend to use a straightforward cut-based analysis. ZZ production provides a major background, but it turns out that because the rate is low, the signal to background achievable for a good candidate in this channel does not exceed that which can be found in the four jet mode.

3.3. τ Channels

The decay of either a Z or a Higgs into a tau pair while the other boson decays hadronically present rather similar features. In order to simplify double counting these two channels may be combined into one for the purpose of extracting the results.

The rates are not large, and if the decay of the Z to all quarks is to be searched for, then b-tagging can no longer be called upon. This means that the background from WW pair production is often serious.

Mass reconstruction is performed using the fact that the neutrino(s) produced in the τ decay can only have a limited p_T with respect to the observed τ decay products. To a good approximation only the two τ energies are unknown, and thus there are 3 over-constraints in the mass fit.

3.4. $H\nu\nu$ Channel

This channel has the extra production process of WW fusion referred to above, but even without that it has the largest rate of the two jet modes. However, the two neutrinos are completely unobserved, and this posses special challenges in the measurement.

The measurement of missing energy in the LEP detectors is rather good, and at LEP 1 this signature was rather clean. For LEP 2 the backgrounds coming from genuine neutrino production have to be taken into account, and furthermore there is a background due to ISR. The emission of a photon from one beam gives rise to missing energy but no missing mass, while emission from both beams can produce large missing mass. The most striking ISR is radiative return to the Z. If this occurs with two photons of approximately equal energy than the visible mass is the Z mass while the missing mass is $\sqrt{s} - M_Z$. This background is unique to this channel, and most important near the kinematic threshold.

In general the jet measurements give the only reliable estimate of the mass of the decaying object. However, if it is assumed that the unobserved, recoiling particles have the mass of the Z, then one constraint can be applied, and this is found to be worthwhile.

3.5. Performance of channels

The data collected are analyzed using a binned maximum likelihood method, where each event is assigned a weight based upon its measured mass, b tag value and kinematic properties. Simulation is used to estimate the expected distributions from background and signal (as a function of Higgs mass) and thus it is possible to estimate the signal to background for any candidate.

We can also find the total number of events expected with a signal to background greater than some cut, and this is a useful indicator of the channels search power. Table 4 contains the expected signal rate (background not shown) for four different cuts in signal to background ratio.

Table 4
Expected signal events for $M_H = 115 GeV/c^2$.

mode	Signal events with s/b			
Higgs Z	> 0.3	> 0.5	> 1	> 3
$b\bar{b}\ \nu\bar{\nu}$	1.7	1.1	0.4	0.06
Any $l\bar{l}$	1.1	0.9	0.7	0.24
tau	0.4	0.3	0.2	0.10
two jets	3.2	2.3	1.3	0.39
four jets	4.1	3.0	1.6	0.36

We see that in general the four jet channels have a higher signal expectation, but that at the very highest levels, thanks to the Hll mode, the two jet channels are slightly more powerful. However, at this point the expected signal strength is only 0.39 events. It is also interesting to observe that the $H\nu\bar{\nu}$ mode, which has the largest rate in two jets, has essentially no chance of finding any event with a signal to background ratio higher than three.

A slightly more precise way to compare the power of the two analyses is to calculate the probability that, in the presence of a signal a 115 GeV/c^2 Higgs they would provide 3 sigma evidence for it. This is 19% for the two jet modes and 24% for the four jet modes, but 45% if they are combined, which is clearly the correct treatment.

3.6. Data collected

There are 3 events found with signal to background larger than 0.5 for $M_H = 115 GeV/c^2$. They are in the $H\nu\bar{\nu}$, Hee and $H\tau^+\tau^-$ channels respectively. Some properties are given in table 5.

Table 5
The most important candidates.

Expt.	$\sqrt{s}$	Z	Mass	s/b
L3	206.4	$\nu\bar{\nu}$	115.0	0.7
ALEPH	205.0	e^+e^-	118.1	0.6
ALEPH	208.1	$\tau^+\tau^-$	115.4	0.5

The $H\tau^+\tau^-$ candidate has a poor kinematic fit, which might suggest that the mass estimate is unreliable. A similar comment can be made about the He^+e^- event, where a one of the electrons, which is close to a jet has a nearby photon. It was decided a priori that in such circumstances the photon should be assigned to the jet, but if it were instead assumed to be brehmstrahlung from the electron the mass would be 99 GeV/c^2.

The $H\nu\bar{\nu}$ event has been controversial. The selection and analysis criteria conclude that it is rather signal like. However one variable which was not considered was the jet collinearity. If this event is forced into two jets, then they have a collinearity of 3.1. The distributions at preselection level in L3 are shown in figure 4. It can be seen the the majority of the signal is not so collinear. However, the a priori analysis did not include that information, and we should therefore not use it to derive results.

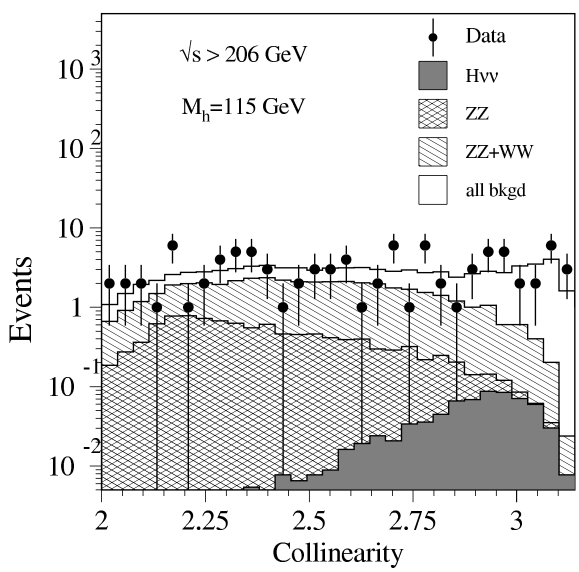

Figure 4. The collinearity of $H\nu\nu$ candidates in L3 are preselection level.

Thus all three of the candidates has some features which are not ideal, but none of them can be said to be definitely not a signal. The statistical analysis is considered in the next section.

3.7. Interpretation

The results are obtained by means of an extended maximum likelihood fit to the observed events. This is done for the combined data set of all four experiments.

The observed results in the two jet channels is shown in figure 5. This shows -2× log likelihood, which will be negative when background is preferred and positive in the case that there is

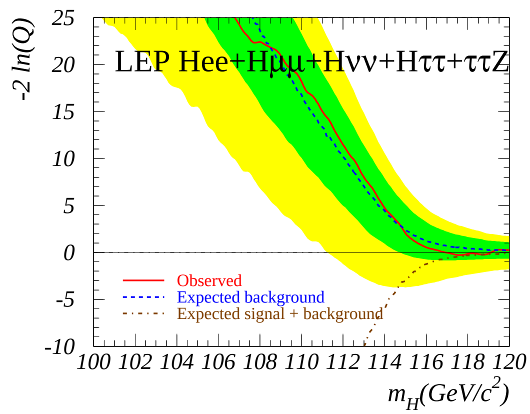

Figure 5. Likelihood (or rather -2× log likelihood) distributions for the three channels.

evidence for a signal. It can be seen that there is no suggestion of a signal. There is a small excess around 118 GeV/c^2, due mainly to the candidate in the Hee channel, but it is not significant.

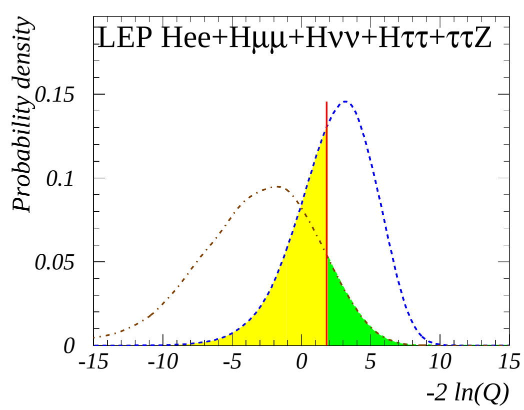

Figure 6. The Likelihood (or rather -2× log likelihood) distributions for the three channels. It can be seen that the distribution favours the background hypothesis.

The limits are set by calculating the probability of obtaining the observed likelihood, or one more extreme. As an example, the likelihood obtained at $M_H = 115\ GeV/c^2$ is compared with the distribution of expected values in figure 6. The integral of the expected distributions up to the line defines CL_b and CL_{sb}, for the case where there is only background, and when a signal is also present. As a conservative step, $CL_s \equiv CL_{sb}/CL_b$ expresses how much less likely the results are when a signal is present.

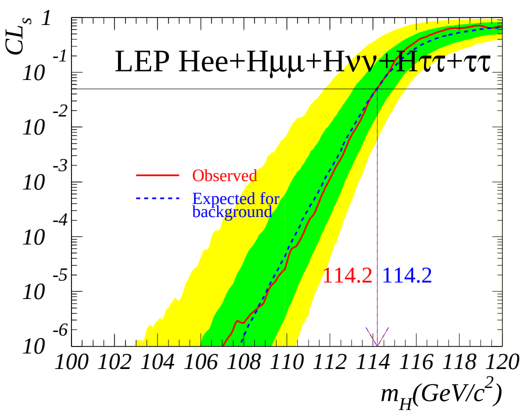

Figure 7. The confidence CL_s, with which a given Higgs mass can be excluded by the two jet channels. For example, all masses below 112 GeV/c^2 are excluded at better than 99.9% confidence.

This is shown in figure 7, where the two jet modes are combined. The observed line matches the expectation very well for all Higgs masses, and at 95% CL we can conclude:

$$M_H > 114.2 GeV/c^2 \quad \text{(two jet modes)} \tag{1}$$

However, the results from the two-jet channel should not be considered in isolation from the four jet results. When they are combined, they provide some evidence for an excess, as can be seen in figure 8.

The level of the excess is slightly more than 2.1 sigmas, and it agrees with the expectation from a signal in terms of signal strength. When we combine the channels, we would expect a limit of around 115.4 GeV/c^2, but due to the excess, we

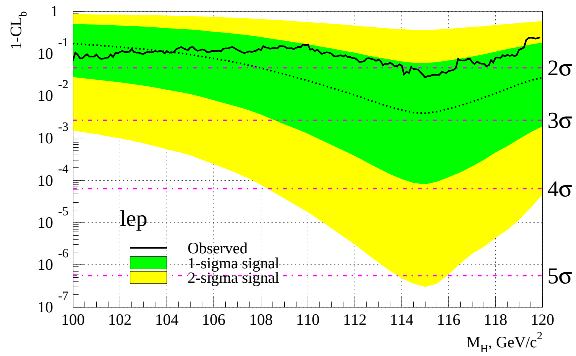

Figure 8. The value of $1 - CL_b$ as a function of the Higgs mass. The dark and light grey bands are the one and two sigma contours for the expectation if a signal of 115 GeV/c^2 is include.

have the unusual result that the observed 95% CL limit decreases to:

$$M_H > 114.1 GeV/c^2 \quad \text{(SM Higgs)} \tag{2}$$

The hint may or may not turn out to be true, but this limit will remain as a major legacy of LEP for some time to come.

As always, this work depended upon the great achievements of the LEP collider team, providing the data and the enthusiasm to pursue it.

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