THE STATUS OF SEARCHES FOR THE STANDARD MODEL HIGGS BOSON AT LEP

presented on behalf of the
OPAL, ALEPH, L3 and DELPHI Collaborations

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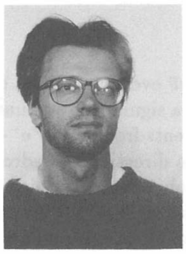

Abstract

In the Standard Model the Higgs mechanism is central to our understanding of how massive fundamental fermions and W and Z intermediate vector bosons can occur within a theory with an underlying $SU(2)\otimes U(1)$ gauge symmetry. The Higgs mechanism predicts the existence of at least one massive fundamental scalar particle, the Higgs boson (H^0). Currently, the most sensitive experimental searches for the H^0 are made at the electron-positron collider LEP at CERN.

Analyses using samples corresponding to 1.9 million hadronic Z^0 decays collected up to the end of 1993 have been presented recently by the OPAL[1)] and ALEPH[2)] Collaborations. In their updated analysis including 1993 data, OPAL have employed exactly the same selection cuts that were used to analyse their 1992 data. In their updated analysis ALEPH have employed an automatic procedure that uses Monte Carlo simulated signal and background events in order choose modified values of the selection cuts such as to perform, for a given collected luminosity, a search with optimal sensitivity. The L3[3)] and DELPHI[4)] Collaborations have presented results based on 1.1 million hadronic Z^0 decays collected up to the end of 1992. Lower limits on the mass of the Standard Model Higgs boson in the range 55–60 GeV have been obtained at 95% CL by all four experiments.

1 Introduction

In high energy electron-positron collisions the H^0 is expected to be produced in association with a virtual Z^{*0} boson via the process shown in figure 1. For an H^0 of mass M_H=60 GeV, the cross section at the Z^0 peak is 0.4 pb and since each LEP experiment has collected an integrated luminosity of 80 pb^{-1} then about 30 H^0Z^{*0} events would have been produced. The experiments search for events in which the H^0 decays to $q\bar{q}$ (branching fraction 93%). The Z^{*0} is detected via its decay to $\nu\bar{\nu}$ (branching fraction 18%) or to e^+e^- or $\mu^+\mu^-$ (branching fraction 3%). The experimental searches are therefore sensitive to 22% (93%x24%) of the produced H^0Z^{*0} events. Taking into account the typical selection efficiencies of 40% then for M_H=60 GeV each experiment would expect to have observed 3 events. Around the Z^0 peak the cross section for $e^+e^-\to q\bar{q}$ is nearly five orders of magnitude higher that that for H^0 production for M_H=60 GeV and very severe cuts are needed against such events in order to be sensitive to the very small signal expected from H^0Z^{*0} production. For H^0Z^{*0} events in which the Z^0 decays to hadrons or in which either the H^0 or Z^0 decays to $\tau^+\tau^-$ a sufficient background rejection cannot be obtained; this is why these decay modes are not used in the experimental searches.

2 The $q\bar{q}\nu\bar{\nu}$ channel

As is illustrated in figure 2(a), $Z^0\to\nu\bar{\nu}$ events present a clear experimental signature, with the two unobserved neutrinos carrying away a significant amount of energy and momentum. The choice of selection cuts to distinguish such events from the $e^+e^-\to q\bar{q}$ background is influenced by the fact that the LEP detectors measure the direction of hadronic jets much more accurately than they measure absolute jet energies. The observed hadronic system is divided into two hemispheres by the plane perpendicular to the thrust axis and a vector sum of the particle momenta is formed separately in the two hemispheres. The principal experimental signature is to require that the two momentum vectors thus formed are not back-to-back. In addition, for a sample of H^0Z^{*0} events the mass of the observed hadronic system $M_{q\bar{q}}$ would be expected to cluster around M_H within the experimental resolution of typically $\pm$10%.

The principal source of background events that survive the above cuts is illustrated in figure 2(b). Events from $e^+e^-\to q\bar{q}$ may contain additional jets due to hard gluon bremsstrahlung. If the energy of one or more of the jets is underestimated such events may fake the acollinear topology expected for the H^0Z^{*0} signal. The energy of a jet may be underestimated due to the presence of a high energy neutrino from the semileptonic decay of a heavy quark $Q\to \nu l X$. Alternatively, the energy of a particle may be mismeasured due to the presence of insensitive regions of the detector or a fluctuation in the detector response. A number of experimental cuts are typically employed in order to remove the background from such events:

- If the energy of a jet is underestimated then the missing momentum vector will point in the direction of this jet. However, since it is very unlikely that every particle in the jet will escape detection, such events can be suppressed by requiring little or no activity to be observed around the direction of the missing momentum.
- If a jet is produced along the beam direction its energy is likely to be poorly measured. Such events can be suppressed by requiring little or no activity to be observed around the beam direction and also by rejecting events in which the missing momentum vector points close to the beam direction. (This cut also rejects events containing hard initial state photon radiation and two-photon production of multihadrons.)

The principal background that survives these cuts consists of events in which the energies of two or more jets have been underestimated. It can be seen that in order to perform such searches it is essential that regions of poor or unreliable detector response are minimized. An example of the requirement that the missing momentum vector be isolated is given in figure 3.

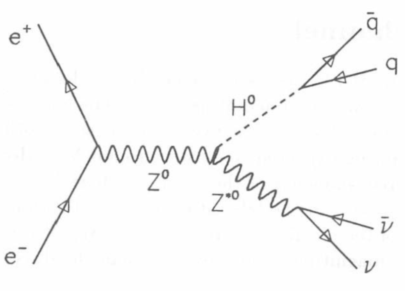

Figure 1: The production mechanism expected for the H^0 in high energy e^+e^- collisions.

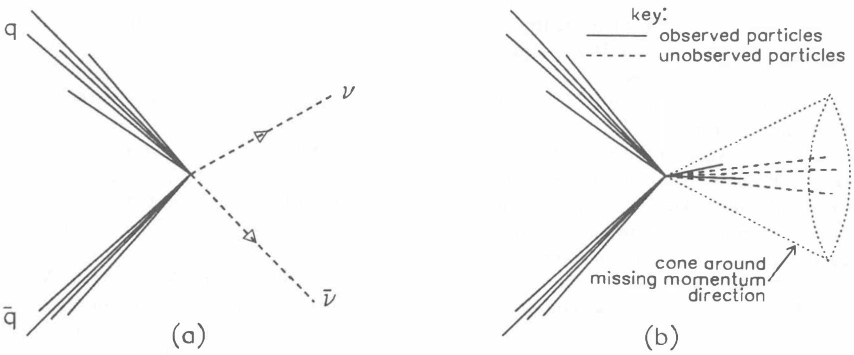

Figure 2: $H^0Z^{*0}\rightarrow q\bar{q}\nu\bar{\nu}$: (a) the experimental signature; (b) an illustration of how jet energy mismeasurement can lead to background.

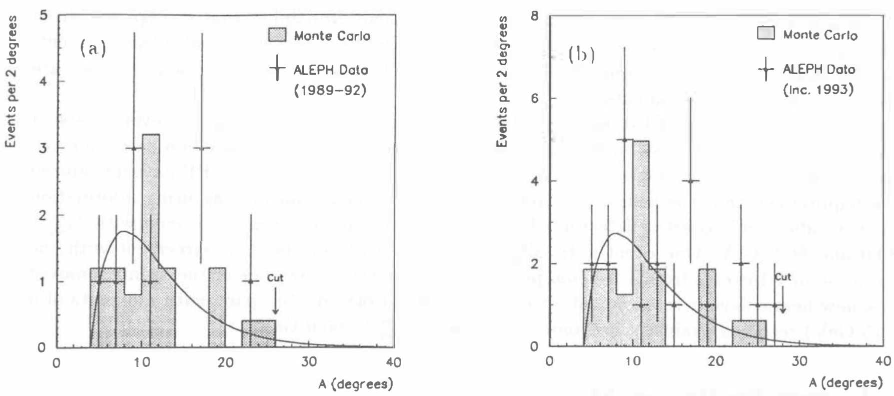

Figure 3: For each event ALEPH find the minimum half-opening angle, A, of a cone around the missing momentum direction that is needed to contain an energy of at least 1 GeV. The angle A is plotted for events passing all other selection cuts: (a) for the previous ALEPH analysis based on data collected up to the end of 1992; (b) for the updated ALEPH analysis based on data collected up to the end of 1993. The expected distribution from a Monte Carlo simulation of background sources is shown as the shaded histogram. The curve shows the fit to the background distribution that is used in the automatic procedure to select the cuts. The positions of the cuts on A employed in the two analyses are also indicated.

3 The $q\bar{q}l^+l^-$ channel

As illustrated in figure 4(a), H^0Z^{*0} events in which the Z^0 decays to a pair of charged leptons (e^+e^- or $\mu^+\mu^-$) also have a clear experimental signature. The leptons are required to be energetic and isolated from the hadronic activity in the event. For a sample of H^0Z^{*0} events the mass of the hadronic system would again be expected to cluster around M_H. However, in the case of $q\bar{q}l^+l^-$ events the precisely measured momenta of the l^+ and l^- together with the assumption that the complete $q\bar{q}l^+l^-$ system is at rest in the laboratory frame with total energy equal to E_{cm} can be used to calculate the mass of the recoiling hadronic system $M_{q\bar{q}}^{recoil}$ with an accuracy of about $\pm1\%$ — i.e., roughly an order of magnitude more precisely than the direct measurement of $M_{q\bar{q}}$ using the observed hadrons. However, in a few percent of events an initial state photon is radiated that causes $M_{q\bar{q}}^{recoil}$ to overestimate the mass of the hadronic system by a GeV or more.

The principal backgrounds arise from the so called '4-fermion' processes, for which the most important diagram is shown in figure 4(b). Additional criteria may be used to distinguish 4-fermion final states from the H^0Z^{*0} signal:

- The lepton pair produced by the bremsstrahlung photon in figure 4(b) will tend to have low invariant mass $M_{l^+l^-}$. In the H^0Z^{*0} events of figure 1 the lepton pair is coupled to the Z^{*0} and tends to have high mass.
- In 95% of the signal events of figure 4(a) the hadronic system produced by the $H^0 \rightarrow q\bar{q}$ decay contains a $b\bar{b}$ pair. However, in the background process of figure 4(b) the $q\bar{q}$ pair is produced in the decay $Z^0 \rightarrow q\bar{q}$. About 22% of $Z^0 \rightarrow q\bar{q}$ decays are to $b\bar{b}$ and since the probability of photon radiation is proportional to the square of the quark charge only about 11% of the 4-fermion background events will contain a $b\bar{b}$ pair.

Figure 5 from OPAL shows, for events passing all other selection cuts, $M_{l^+l^-}$ versus $M_{q\bar{q}}$ for (a) the OPAL data and (b) a sample of 4-fermion Monte Carlo[5] events corresponding to an integrated luminosity 100 times that of the data. One high mass candidate event is found in the OPAL data. The event is shown in figure 5(c). The $\mu^+\mu^-$ pair is extremely well isolated; no tracks or clusters are found within 30° of either muon. The mass of the recoiling hadronic system is 61.2 ± 1.0 GeV. One of the jets contains a secondary vertex displaced by 4.4 standard deviations from the primary e^+e^- interaction point; this indicates a high probability that it originated from a heavy quark. From figure 5(b) it can be seen that the 4-fermion process can also lead to events in the region of the candidate event. For $M_{q\bar{q}}^{recoil}>50$ GeV 0.5 events from 4-fermion processes are expected to pass the selection cuts.

Figure 6(a) shows for ALEPH data including 1993, the distribution of $M_{q\bar{q}}^{recoil}$ for events passing all the other selection cuts used in the previous ALEPH analysis that was based on data collected up to the end of 1992. Three events with $M_{q\bar{q}}^{recoil}>50$ GeV are observed and ALEPH have introduced a new requirement that the hadronic system satisfy a loose heavy flavour tag using information from their silicon microvertex detector. This new requirement removes two events with $M_{q\bar{q}}^{recoil}$ of 60.0 and 66.0 GeV. One event with $M_{q\bar{q}}^{recoil}=51.4\pm0.5$ GeV survives, in agreement with the expectation of 1.1 events from 4-fermion processes. Figure 6(b) shows one of the events removed by the new heavy flavour requirement. It contains a well isolated e^+e^- pair (with momenta of 9 and 15 GeV) recoiling against a hadronic system with $M_{q\bar{q}}^{recoil}=60.0$ GeV.

4 Lower limits on M_H

Table 1 summarizes the results of the current searches. For each of the four experiments are given: the data sample currently analysed; the value of $M_{q\bar{q}}$ for each candidate event with $M_{q\bar{q}}>40$ GeV in the $\nu\bar{\nu}$, e^+e^- and $\mu^+\mu^-$ channels; and the resulting 95% confidence level lower limits on M_H†.

For OPAL, in the presence of one candidate event the 95% CL lower limit is set at 4.7 ex-

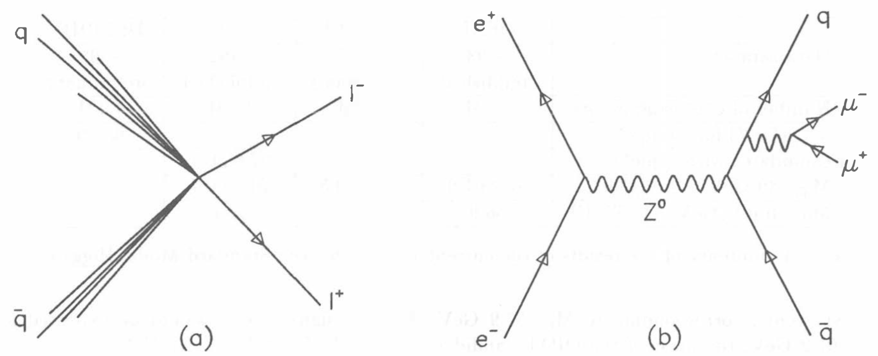

Figure 4: $H^0Z^{*0} \rightarrow q\bar{q}l^+l^-$: (a) the experimental signature; (b) the 4-fermion process.

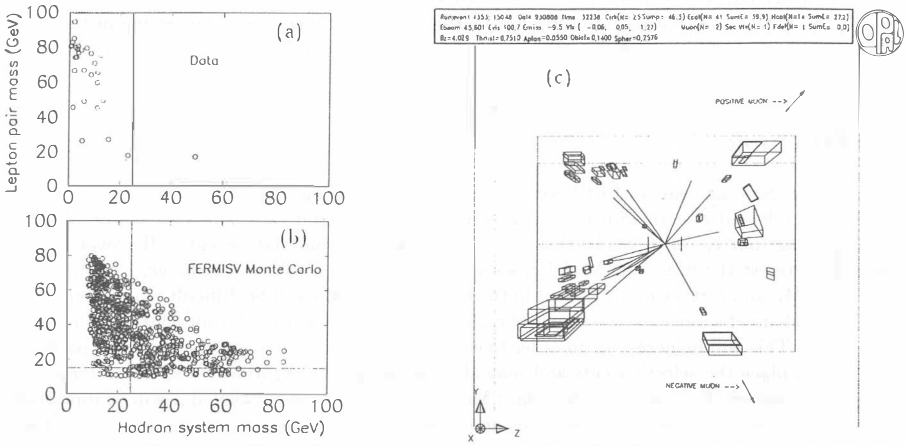

Figure 5: OPAL $q\bar{q}l^+l^-$ analysis: $M_{l^+l^-}$ versus $M_{q\bar{q}}$ for (a) data and (b) 4-fermion Monte Carlo[5]; (c) candidate $q\bar{q}l^+l^-$ event with $M_{q\bar{q}}^{recoil}$=60.0 GeV.

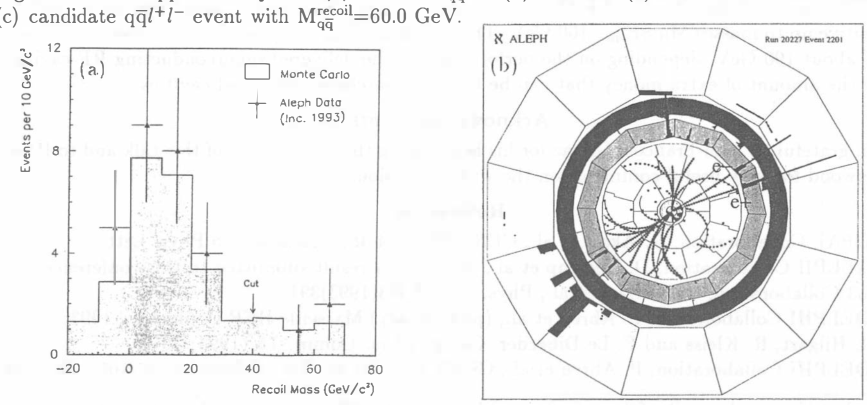

Figure 6: ALEPH $q\bar{q}l^+l^-$ analysis: (a) $M_{q\bar{q}}^{recoil}$; (b) a $q\bar{q}l^+l^-$ event removed by the new heavy flavour tag requirement of ALEPH.

		OPAL	ALEPH	L3	DELPHI†
Data sample		→93 published	→93 preliminary	-→92 published	-→92 preliminary
Number of $e^+e^- \to q\overline{q}$ events		1.9M	1.9M	1.1M	1.1M
$M_{q\overline{q}}$ (GeV) for	$q\overline{q}\nu\overline{\nu}$	—	—	—	68±9
candidates with	$q\overline{q}e^+e^-$	—	—	67.6±0.7	—
$M_{q\overline{q}}$>40 GeV	$q\overline{q}\mu^+\mu^-$	61.2±1.0	51.4±0.5	70.4±0.7	—
Mass limit (GeV) @ 95% CL		56.9	60.3	57.7	55.5

Table 1: A summary of the results of the current searches for the Standard Model Higgs boson.

pected events, corresponding to M_H>56.9 GeV. About 2 signal events would be expected for M_H=61.2 GeV, the mass of the OPAL candidate. For ALEPH, at M_H=51.4 GeV, the value of $M_{q\overline{q}}^{recoil}$ for the ALEPH candidate, the number of expected signal events would be 13. Because $M_{q\overline{q}}^{recoil}$ is measured with a resolution of ±0.5 GeV this event is completely inconsistent with an $M_{q\overline{q}}$ in the region of 60 GeV and therefore the event has no influence on the setting of the mass limit. Thus, the 95% CL lower limit for M_H is set at 3.0 expected events, corresponding to M_H>60.3 GeV.

5 Outlook

In the two remaining years of LEP1 we can anticipate something like a three-fold increase in the number of collected Z^0s. In addition, work is in progress to understand how best to combine the results of the four experiments in the presence of observed candidate events. However, in the region of interest the Standard Model cross section for H^0Z^{*0} production falls very steeply with increasing M_H and further improvement in the lower limit on M_H will be difficult. In particular for the $q\overline{q}l^+l^-$ channel a more accurate prediction for the level of background from 4-fermion processes is required. This will be necessary in order to evaluate in an unbiassed way the optimum positions at which to place the selection cuts and may allow a background subtraction to be performed in the $q\overline{q}l^+l^-$ channel. Even after the Standard Model search has been exhausted it will be important to continue looking for events of the types described in this note in order to be sensitive to their production at a lower rate than that predicted for a Standard Model Higgs boson.

Attention will then turn to LEP2, where searches for the Standard Model Higgs boson will be sensitive up to masses $M_H \approx E_{cm} - 100$ GeV. The maximum E_{cm} will probably lie between 175 GeV and about 190 GeV, depending on the performance of the delivered superconducting RF cavities and the amount of extra money that can be found to purchase additional cavities.

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References

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†The table gives the results of the preliminary analysis from DELPHI that were available at the time of this talk. Shortly afterwards DELPHI produced an updated analysis[6] of their 1992 data in which the high mass candidate in the $q\overline{q}\nu\overline{\nu}$ channel was eliminated and the mass limit was increased to M_H>55.7 GeV.