Search for the Standard Model Higgs Boson at LEP

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Preliminary results from the four LEP experiments using data collected at 189 GeV have shown no evidence for the Standard Model Higgs boson. The preliminary 95% confidence level lower limits on the SM Higgs boson mass from ALEPH, DELPHI, OPAL, and L3 are 90.4 GeV/c^2, 94.1 GeV/c^2, 95.5 GeV/c^2, and 95.2 GeV/c^2, respectively. When LEP finishes in the year 2000, each experiment expects to collect 200 pb^{-1} of data at 200 GeV. These data will allow the discovery of the SM Higgs boson with a mass lower than about 105 GeV/c^2. Assuming that no new evidence for the SM Higgs boson is found, the mass exclusion limit would be approximately 110 GeV/c^2.

I. INTRODUCTION

The objectives of my talk are to present current LEP limits on the mass of the Standard Model (SM) Higgs boson using data from 1998 taken with a center-of-mass energy of 189 GeV, and to predict, using all of the expected data taken by LEP through the year 2000, the discovery potential and final Higgs boson mass limit, assuming no evidence is found.

Although the Standard Model has had tremendous success in explaining all known particle physics measurements, the exact mechanism by which the masses of the vector bosons and fermions are generated is still not understood. The Glashow-Weinberg-Salam theory describes a mechanism which generates particle mass through interactions of the particle with a scalar field [1]. This Higgs field would manifest itself as a neutral spin-0 boson called the Higgs boson.

The Glashow-Weinberg-Salam theory predicts all aspects of the Higgs boson, except for the Higgs boson mass. Electroweak observables do, however, depend upon the Higgs boson mass through logarythmic corrections. Recent precision measurements of the top quark mass, $\sin^2\theta_W$, and the W boson mass, indicate a light Higgs mass near 100 GeV/c^2 and a 95% confidence level upper mass limit of 262 GeV/c^2 [2]. Although highly uncertain, this electroweak measurement is exciting since it is at the threshold of the current mass limits on the Higgs boson.

II. HIGGS BOSON PRODUCTION AND DECAY

Since the coupling strength of the Higgs boson to other particles is proportional to the particle's mass, the Higgs boson is produced by coupling to heavy particles, of which the heaviest known particle produced at LEP2 is the Z boson. As a consequence, the main production mechanism for Higgs bosons at LEP2 is the Higgs-strahlung process $e^+e^- \rightarrow Z^* \rightarrow HZ$ where the Higgs boson is emitted from the Z boson line [3]. The other Higgs boson production channels at LEP2 are the WW and ZZ fusion processes which produce a final state with a pair of electron neutrinos or electrons, respectively. In these fusion processes, the Higgs boson is formed in the collision of two quasi-real W or Z bosons radiated from the electron and positron beams. Interference between the production processes with electron neutrinos or electrons in the state are taken into account [4].

The radiatively corrected cross sections for the Higgs-strahlung process and the sum of the two fusion processes including the interference terms are shown in Figure 1 as a function of the Higgs boson mass for a center-of-mass energy of 188.6 GeV. The rapid fall off in the cross section for the Higgs-strahlung process at a Higgs boson mass of 95 GeV/c^2 is due to the diminishing phase space available to produce both the heavy Higgs boson and an on-shell Z boson.

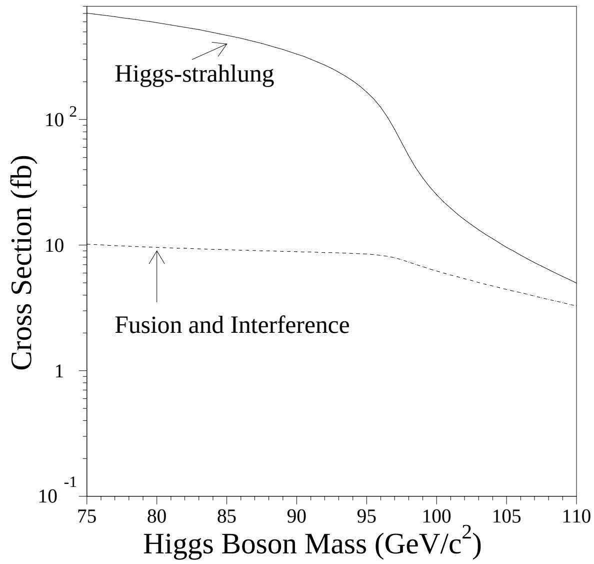

FIG. 1. The Higgs boson cross section as a function of Higgs boson mass for the Higgs-strahlung process, and the sum of the WW and ZZ fusion processes and the interference terms.

In the Higgs boson search region of interest from masses of about 85 GeV/c^2 to 100 GeV/c^2, the decay of the Higgs boson into pairs of top quarks, Z bosons, or W bosons is not kinematically accessible. Consequently, the Higgs boson, which couples to mass, will most likely decay into the next heaviest set of particles which are the b quarks, τ leptons, and c quarks in order of decreasing mass. Figure 2 shows the nearly mass independent branching ratios of the decay of the Higgs boson as a function of its mass. The dominant decay to b quarks comprises about 85% of all Higgs boson decays, while the decay to τ leptons provides another 8% to the total branching fraction. The searches at LEP2 consider the Higgs boson decaying to b quark pairs or τ lepton pairs only, as these two channels comprise 93% of the total Higgs branching fraction.

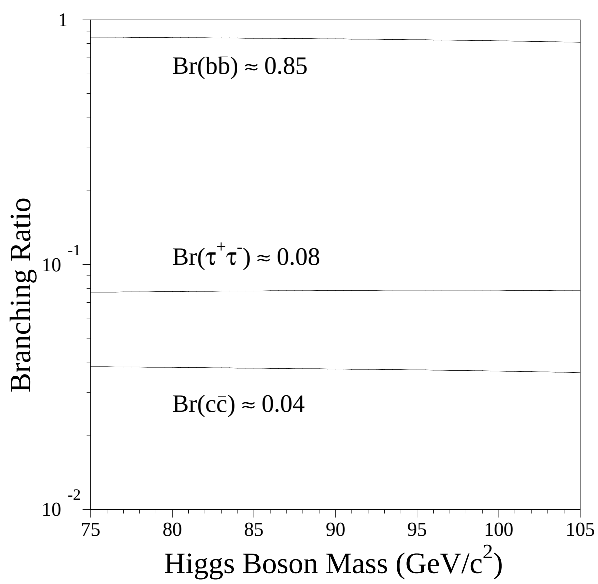

FIG. 2. The branching ratios of the decay of the Higgs boson into b quarks, τ leptons, and c quarks as a function of the Higgs boson mass.

III. HIGGS BOSON TOPOLOGIES

The four LEP collaborations have searched for the Standard Model Higgs boson in all of the possible decays of the Higgs boson ($\mathrm{b\bar{b}}$, $\tau^+\tau^-$) and the Z boson ($\mathrm{q\bar{q}}$, $\nu\bar{\nu}$, $\mathrm{e^+e^-}$, $\mu^+\mu^-$, $\tau^+\tau^-$). Most of the backgrounds with large cross sections are easily reduced leaving the more difficult backgrounds which, fortunately, have cross sections not much larger than the Higgs boson signal. The most difficult background for all topologies is the ZZ final state. This irreducible background occurs when one Z boson decays to $\mathrm{b\bar{b}}$ or $\tau^+\tau^-$ and m_H is approximately equal to m_Z. The high purity of the selections and the large amount of collected luminosity per experiment allows this difficult ZZ barrier to be overcome.

A. Four Jet Topology

The four jet final state, where the Higgs boson decays to b quarks and the Z boson decays to any quark pair, comprise 64.6% of the Higgs boson final states. Difficult backgrounds for this topology include four jet WW events with four well defined, isolated jets. This background is significantly reduced by b-tagging the two jets in the event associated to the Higgs boson. Another difficult background arises from b quark pair production with a radiated high energy gluon. B-tagging is not effective for this background, and kinematics must be used to distinguish jets arising from the Z boson decay in the signal and jets from the high energy gluon. Typical selection efficiency for this channel is about 40%.

B. Missing Energy Topology

The missing energy topology where the Higgs boson decays to b quarks and the Z boson decays to neutrinos comprises 20.0% of the Higgs boson final states. A difficult background for this topology arises from b quark pair production with two or more high energy initial state radiated photons going undetected down the beam. Cuts on kinematic variables like the acoplanarity of the b jets and the transverse momentum of the event are used to remove this difficult background that is both b-tagged and has a large missing mass. Typical selection efficiencies for the missing energy channel is about 40%.

C. Lepton Pair Topology

The leptonic final state where the Z boson decays to either an electron or muon pair comprises only 6.7% of the total Higgs boson final states, but this final state achieves high purity with the ablility to precisely reconstruct the Z boson. This allows the reduction of all backgrounds except the irreducible ZZ final state. High purity of the channel also allows sensitivity to the decay of the Higgs boson to both b quarks and τ leptons which are typically reconstructed as the recoil to the lepton pair. Typical selection efficiency for this channel is typically about 75%, where the largest losses are due to the charged particle tracking acceptances of the detectors, and the insensitivity of the selection to off-shell Z bosons.

D. Tau Pair Topology

The most difficult channel is the final state containing two jets and a pair of τ leptons. This final state arises from either the decay of the Higgs boson to b quarks and the Z boson to τ leptons or the decay of the Higgs boson to τ leptons and the Z boson to any quark pair. The combined branching fraction of these two final states is 8.7%. When no b-tagging can be applied, as in the second case were the Z boson decays into all quark flavors, a difficult background arises from the $\mathrm{W^+W^-}$ process where one W decays to a τ and a neutrino. Since τ identification is difficult, another charged particle in the event is often identified as the decay of the other τ lepton, and rejection of these types of events relies upon tight kinematic constraints on the final state consistent with HZ production. The typical selection efficiency for this channel is generally less than 30%.

IV. LIMITS ON THE HIGGS BOSON MASS

Both the expected and observed Higgs boson lower mass limits at 95% confidence level for each of the LEP experiments are summarized in Table I. These preliminary results include all of the data collected at a center-of-mass energy of 189 GeV and were made immediately after the end of the physics data taking period of 1998. Consequently, all of these limits are considered highly preliminary and likely to change.

Figure 3 shows, as an illustration, the preliminary expected and observed limits from the DELPHI collaboration as a function of the Higgs boson mass. The intersection of the limits with the 5% line define the exclusion region with 95% confidence. The expected and observed limits from the four collaborations are in fair agreement indicating the lack of a signal from the Standard Model Higgs boson.

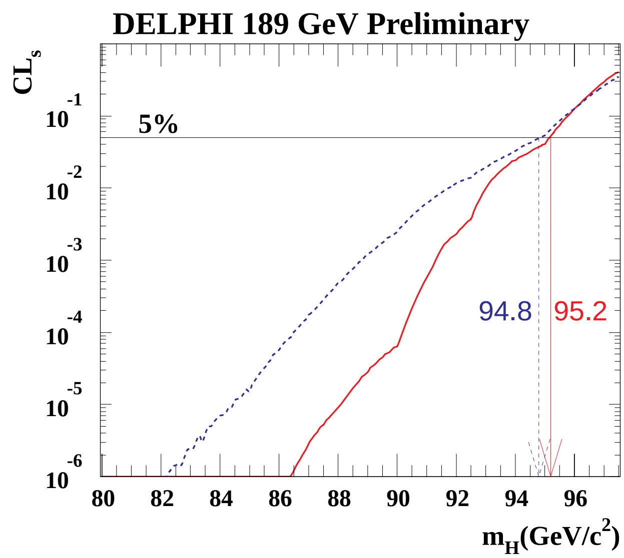

FIG. 3. The configurations of external legs that are summed over.

The similar expected limits for the four collaborations indicate the similar capabilities of the different detectors. Variations in observed limits are mostly due to the uncertainties involved in low statistics. The low ALEPH observed limit could be indication of a Higgs boson signal, but, considering the limits of the other experiments, the low limit is most likely due to unluckiness preventing the ALEPH limit from overcoming the ZZ final state barrier.

TABLE I. Preliminary expected and observed limits on the Standard Model Higgs boson mass at 189 GeV.

Experiment	Expected Limit	Observed Limit
ALEPH [5]	95.7 GeV/c^2	90.2 GeV/c^2
DELPHI [6]	94.8 GeV/c^2	95.2 GeV/c^2
L3 [7]	94.5 GeV/c^2	95.5 GeV/c^2
OPAL [8]	95.2 GeV/c^2	94.0 GeV/c^2

V. PROSPECTS FOR THE END OF LEP

By the end of the LEP program in the year 2000, each experiment is expected to have received about 200 pb^{-1} of data with a center-of-mass energy of 200 GeV. Figure 4 shows the discovery potential and expected limit for the Standard Model Higgs boson as a function of the luminosity for each experiment [9]. The figure assumes that the limits from all four LEP collaborations will be combined. The figure is an overly optimistic expectation for LEP performance since it is made assuming a center-of-mass energy of 205 GeV which is probably unattainable. To account for the higher center-of-mass energy, a few GeV/c^2 should be subtracted from the Higgs boson mass to obtain realistic expectations. The figure indicates that with 200 pb^{-1} of data per experiment, LEP2 should be able to discover a Standard Model Higgs boson with a mass less than about 105 GeV/c^2. Assuming no new evidence for the Higgs boson, exclusion limits at 95% confidence level will set a minimum mass on the Standard Model Higgs boson at about 110 GeV/c^2.

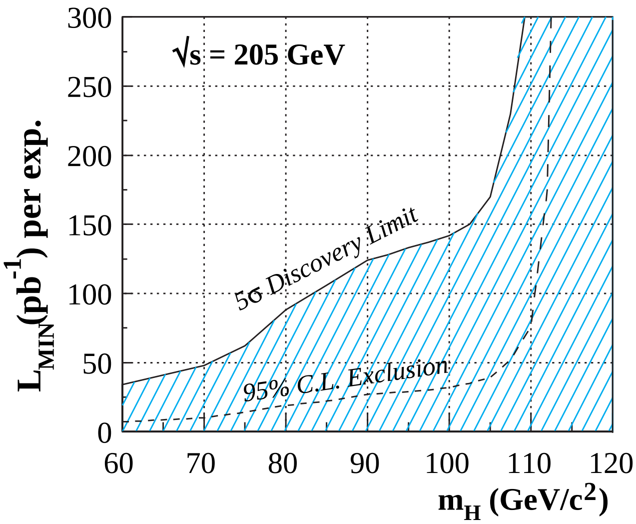

FIG. 4. Discovery and exclusion potential of the combined LEP experiments as a function of the collected luminosity per experiment for a center-of-mass energy of 205 GeV.

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