Search for neutral Higgs bosons decaying into four taus at LEP2

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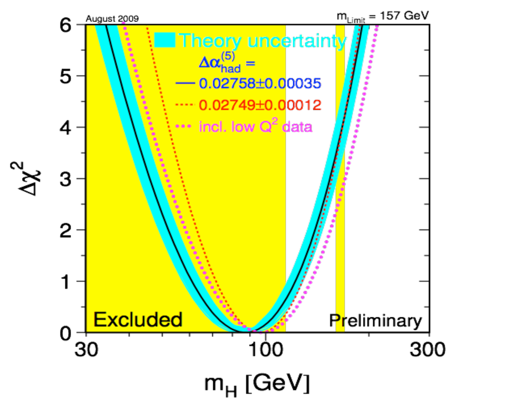
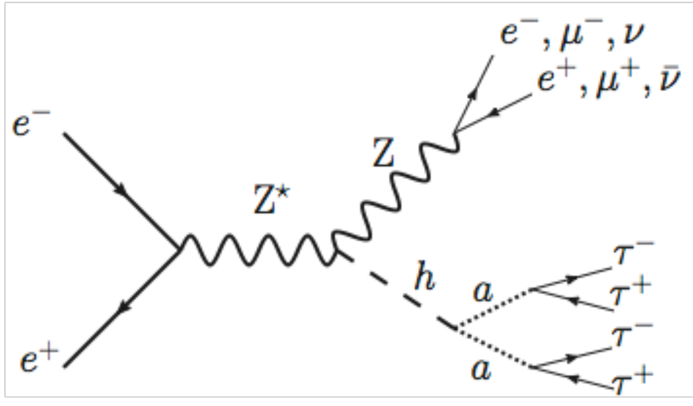
Motivation and Previous Limits

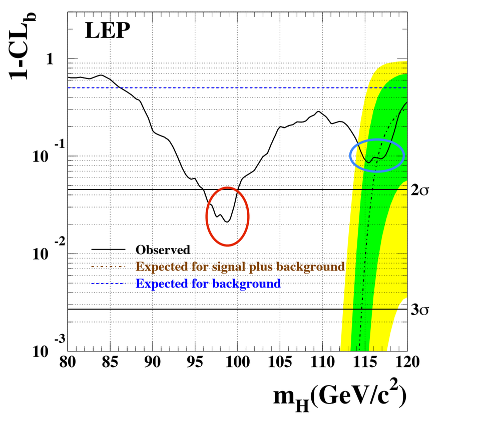
Direct searches at LEP placed a lower bound on the Higgs mass of 114 GeV/c^2 [1]. However, EW fits to the Standard Model prefer a light Higgs mass.



Preferred goodness-of-fit values of EW precision data to the Standard Model vs. Higgs mass.

Additionally, LEP saw a suggestive excess at ~98 GeV/c^2, consistent with models with naturally light states, *a*, such as the NMSSM [2]. In these models, $h \to aa$ can dominate over $h \to b\bar{b}$, and for $m_a < 2m_b$, the subsequent decay of the *aa* pair would **evade 4*b* searches and one would expect** $a \to \tau^+\tau^-$.



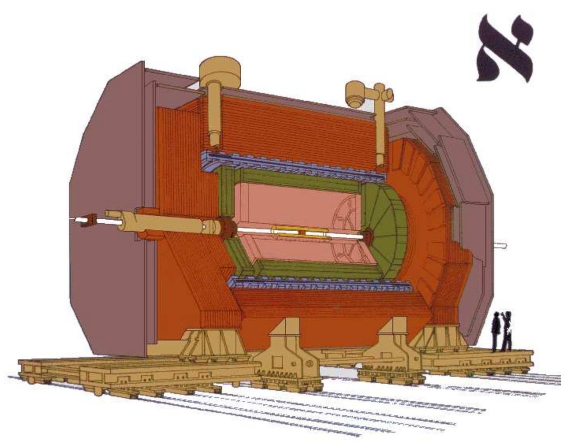


The excess in LEP data at ~114 GeV/c2 (blue) is Standard Model-like, while the excess at ~98 GeV/c2 is non-SM-like.

A previous OPAL search [3] was restricted to $m_h < 86$ GeV/c^2, for $2 m_\tau < m_a < 11$ GeV/c^2, and thus **the range 86 < m_h < 114 GeV/c^2 is not covered by existing analyses**.

The ALEPH Detector

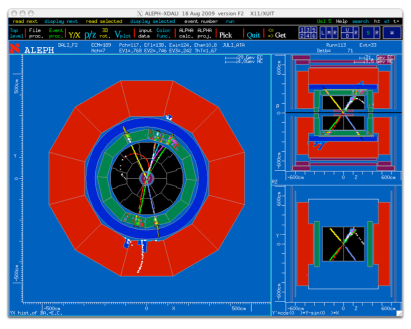
High momentum resolution is achieved via a large tracking volume immersed in a 1.5 T magnetic field. An energy-flow reconstruction algorithm provides a list of objects which are classified as charged particles, photons, and neutral hadrons, and which are the basic entities used in the present analysis. See [4] for a full description.



The ALEPH Detector

During LEP2 the machine operated at centre-of-mass energies from 183 to 209 GeV and collected data corresponding to a total integrated luminosity of 683 pb^{-1}.

Signal and background samples

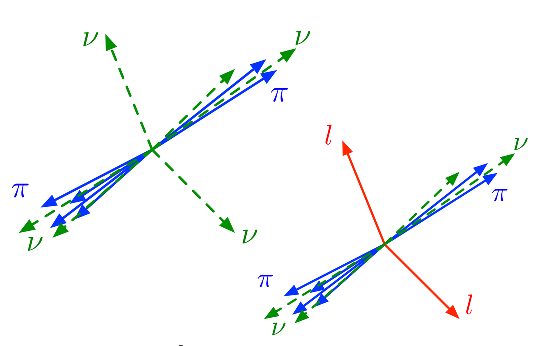


A simulated signal event with $Z \to e^+e^-$ and $aa \to \tau^+\tau^-\tau^+\tau^-$.

All steps of the ALEPH analysis framework were revived, including the ability to generate simulated samples of standard model background and data. We produced 3000 simulated signal events (with $h \to aa$ followed by $a \to \tau^+\tau^-$) for each of the three *Z* decay channels considered and for each combination of Higgs boson and *a* masses in the ranges $70 < m_h < 114$ GeV/c^2 and $4 < m_a < 12$ GeV/c^2 in steps of 2 GeV/c^2. For the relevant background processes, our samples were either 10-30 or 300-1000 times larger than the data, depending upon the process.

Reconstructing $a \to \tau^+\tau^-$ jets

For the mass range considered, the Higgs is produced approximately at rest, and thus the decay $h \to 2a \to 4\tau$ results in a pair of taus recoiling against another pair of taus. For the mass range considered, the decay products of each 2τ system will be observed as a highly-collimated jet of charged particles. Due to this high level of collimation, individual identification of taus, via standard algorithms, would fail. Instead, the fact that each τ decays into either one charged particle or three charged particles was used, and one would thus expect each *a* jet to contain two, four or six tracks. The JADE algorithm was employed to form jets with a ycut chosen to merge proto-jets up to a mass of $m_{jet} = 15$ GeV/c^2.



Selection Criteria

We considered two possible decay classes of the *Z* boson -- namely $Z \to l^+l^-$ (where *l* = *e* or *μ*) and $Z \to \nu\bar{\nu}$ -- and formulated a set of loose selection criteria (convenient to allow comparison of data and simulation at an intermediate stage without compromising the blind nature of the analysis) and final selection criteria.

$Z \to l^+l^-$

For the $Z \to l^+l^-$ channel, four-fermion processes are a prominent background. We used ALEPH lepton identification algorithms to mask the two most energetic leptons in the event from the list of objects clustered by the JADE jet-finding algorithm.

Loose selection:

- 2 oppositely charged, isolated leptons
- 2 jets, well-contained within tracking volume $|\cos\theta_j| < 0.9$
- jets and leptons sufficiently isolated from each other $|\cos\theta_{jl}^{min}| < 0.95$

Final selection:

- invariant mass of lepton pair near Z mass $80 < M_{l^+l^-(\gamma)} < 102\ \mathrm{GeV}/c^2$
- some missing energy (from neutrinos from tau decays) $\not{E} > 20$ GeV
- jets separated $\cos\theta_{jj} < 0$
- signal-like track multiplicity $n_{1,2}^{trk} = 2$ or 4

@ loose selection	data	background
Z > e+ e-	299	332
Z > μ+ μ-	83	75

$Z \to \nu\bar{\nu}$

The $Z \to \nu\bar{\nu}$ channel represents a larger branching ratio of the *Z* than the lepton channel. A major background contribution arises from two-photon-initiated events.

Loose selection:

- missing energy and mass $\not{E} > 30$ GeV $\not{m} > 20\ \mathrm{GeV}/c^2$
- exactly 2 jets, well-contained $|\cos\theta_j| < 0.85$ $m_{jj} > 10\ \mathrm{GeV}/c^2$
- reject "2 photon" and beam background events $|\cos\theta_{miss}| < 0.9$ $E_{vis} > 0.05\ E_{CM}$
- requirements on most energetic jet $E_{j_1} > 25$ GeV $n_1^{trk} = 2$ or 4

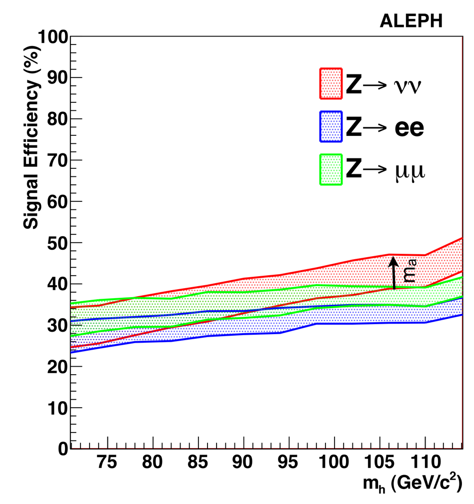
@ loose selection	data	background
Z > νν	206	200

Final selection:

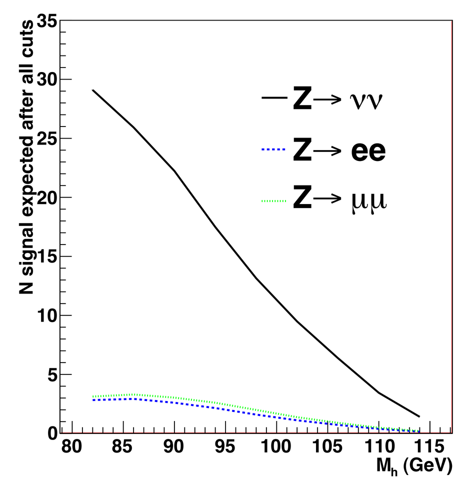
- less than 5 GeV within 30° of beam axis
- consistency with $Z \to \nu\bar{\nu}$: $\not{E} > 60$ GeV and $\not{m} > 90\ \mathrm{GeV}/c^2$.
- small aplanarity (<0.05) consistent with 2 back-to-back, highly collimated jets
  - signal has higher aplanarity for high m_a and low m_h: cut chosen to maintain efficiency
- signal-like track multiplicity $n_{1,2}^{trk} = 2$ or 4

Signal Efficiency and Expected Yield

Based upon the selection criteria above, our signal efficiency ranged from ~25% to ~50%, depending on Z decay channel, Higgs mass, and a mass. We determined that, for the $Z \to l^+l^-$ channel, we should expect ~3 signal events versus < 0.2 background events, and for the $Z \to \nu\bar{\nu}$ channel our expectation was ~11 signal events versus ~6 background events.

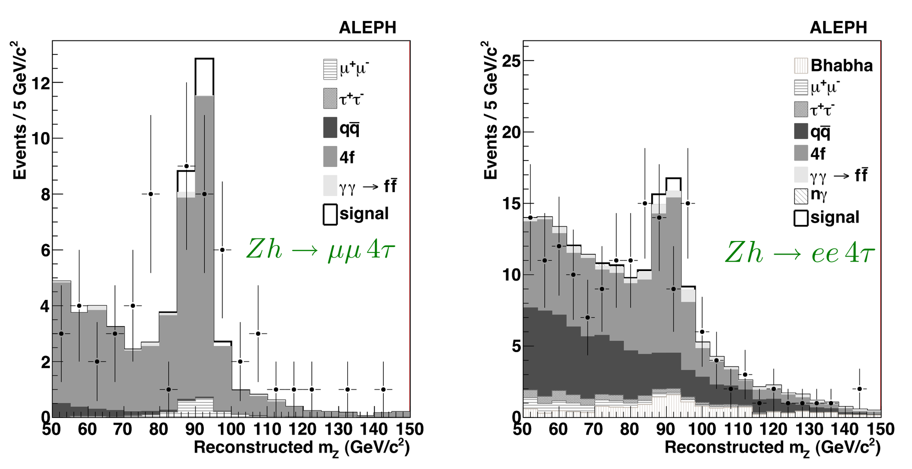


Signal efficiency as a function of Higgs mass for the three Z decay channels considered.



Expected number of events after application of all selection criteria.

Systematics and Results at Loose Selection

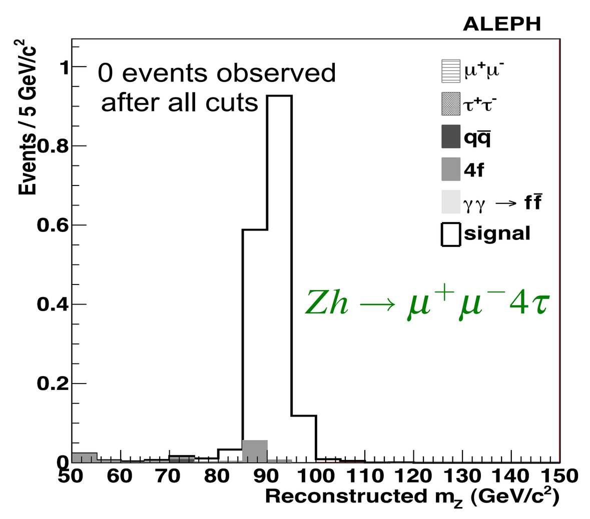


Reconstructed Z mass for the Z → l+l– channels after applying the loose selection criteria detailed above.

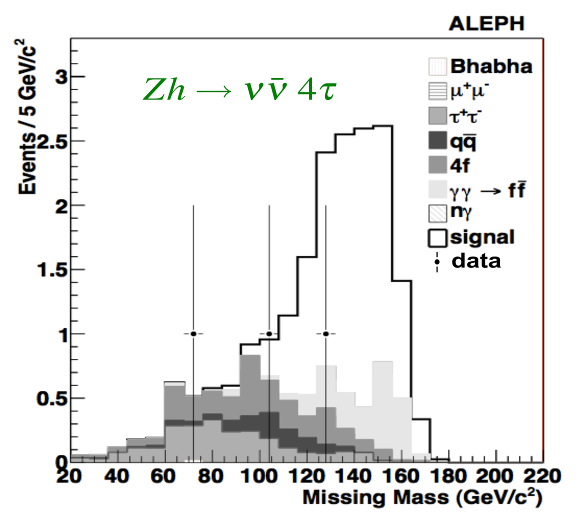
Systematic uncertainties in our Monte Carlo simulation were estimated to be 5% for all signal and 10% for background in the $Z \to l^+l^-$ channel versus 30% for background in the $Z \to \nu\bar{\nu}$ channel. We found that the background estimate and the number of events seen in data at the loose selection agreed within the systematic and statistical uncertainty for all *Z* channels.

Final Results and Limits

For the $Z \to l^+l^-$ channels, **zero events** were observed after applying all selection criteria, while for the $Z \to \nu\bar{\nu}$ channel **two events** were observed. These observations are consistent with background.



Reconstructed Z mass for one of the Z → l+l– channels (here for muons) after all selection criteria. Zero events were observed.

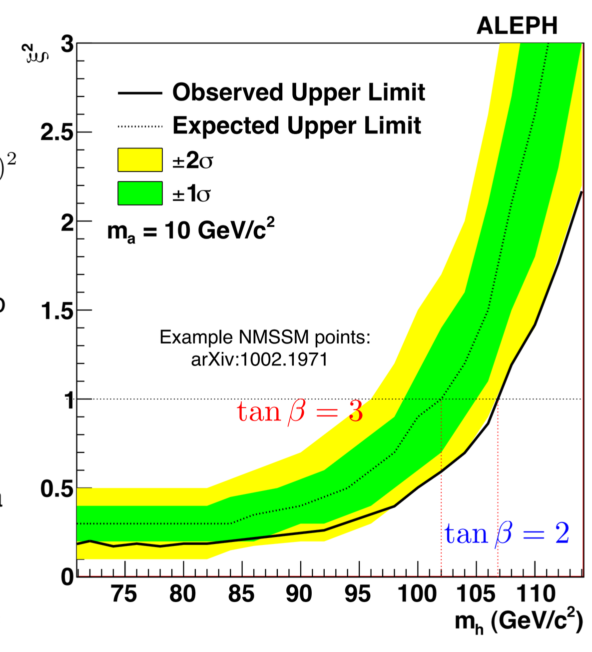


Marginal distribution for the missing mass for the Z → νν channel after all selection criteria. Two events were observed; the data point at ~71 GeV/c^2 is excluded after application of the missing mass cut.

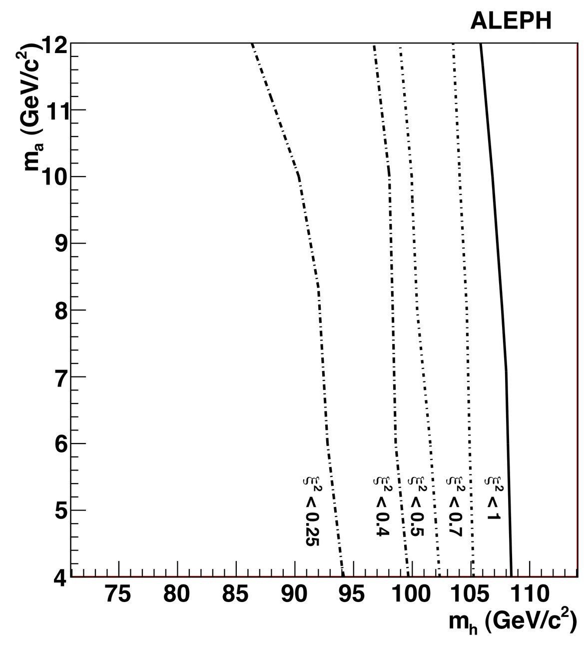
Limits are placed upon the cross section times branching ratio of our signal process with respect to the SM Higgsstrahlung production cross section,

$$\xi^2 = \frac{\sigma(e^+e^- \to Zh)}{\sigma_{SM}(e^+e^- \to Zh)} \times B(h \to aa) \times B(a \to \tau^+\tau^-)^2$$

based upon event counts in three separate track multiplicity bins (corresponding to events with two jets where 1) each jet contains two tracks, 2) each jet contains four tracks, or 3) one jet contains two tracks while the other contains four tracks) times each of the three Z decay channels considered, resulting in nine categories. The resulting joint probability density for the event counts is then used to construct confidence intervals using a generalized version of the Feldman-Cousins technique [5], which incorporates systematic uncertainties in a frequentist way [6][7]. Results are shown, for the 95% confidence level, as a function of m_h (for m_a = 10 GeV/c^2) in the left figure and as contours within the m_h, m_a plane on the right.



Observed and expected 95% CL limit on ξ^2 as a function of m_h for m_a = 10 GeV/c2. Also shown are some favored point in the parameter space of the NMSSM.



Contours of observed 95% CL limit on ξ^2 in the m_h, m_a plane.

Also shown in the left figure is the effect of these results upon some possible favored scenarios in the NMSSM; see [8], Figures 17 and 21 therein. Our limits highly constrain scenarios with tan β ≥ 3, while scenarios with tan β ≤ 2, where there is a larger branching ratio of the *Z* boson into jets, remain unconstrained.

References:

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