LEP Higgs

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LEP had long been the only place where the Higgs boson could be unambiguously searched for. As the LEP experiments verified the gauge interactions more and more rigorously, searches for the Higgs boson, which forms the very basis of the gauge theories, were taking on more and more importance in LEP physics. How this last missing particle in the Standard Model may be discovered (or totally excluded) will be the key to new physics beyond the Standard Model. Here I briefly describe how the LEP experiments together have closed in on this God particle during their 11 year running.

1 Introduction – Higgs before LEP

How beautifully they may describe the interactions among the fermions and the vector bosons, the gauge theories would break down, if the Higgs boson or its equivalent, which must have caused the phase transition of the vacuum of our universe immediately after the Big Bang, does not exist. However, prior to the LEP experiments, direct experimental constraints on the Higgs boson were few and many of them suffer from theoretical uncertainties.[1] Here I quote just a few of the experimental limits that had been available before LEP. Theoretical thoughts on the Higgs mass at the time are also briefly reviewed.

Experimental Bounds before LEP

The Higgs boson was searched for in the decays of the bottom quarks, the heaviest particles at the time, because it couples more strongly to heavier particles. The CUSB collaboration looked for the decay $\Upsilon \to H\gamma$ and excluded a Higgs of up to 5–6 GeV.[2] It turned out that first order QCD corrections reduce the lowest order calculation by about 50%, and the effects of higher order corrections or relativistic corrections were not known. CUSB also searched for Υ decays to a photon plus a massless, invisible scalar. The Crystal Ball collaboration looked for J/ψ decays to a photon plus a massless scalar[3]. These two results together excluded a massless and very light Higgs, which is also subject to radiative correction uncertainties. The JADE and CLEO collaborations each provided bounds on the branching ratio of $B \to \mu^+\mu^- X$.[4] They were translated into the limits on a Higgs in the region 0.3 – 3.5 GeV but with large uncertainties in the Higgs branching ratio into a muon pair.

The electron beam dump experiment, searching for the process $e^- \to e^- H \to e^- e^+ e^-$, excluded the region 1.2 – 52 MeV (90% C.L.), free of theoretical ambiguities.[5] The SINDRUM collaboration measured the decay $\pi^+ \to e^+\nu_e e^+ e^-$, which gave limits on the production of a very light Higgs via the process $\pi^+ \to e^+\nu_e H$. They excluded the mass region 10 – 110 MeV with some theoretical uncertainties related to the gluonic content of the pion.[6] Other experiments that searched for light Higgs bosons include studies of transitions in muonic atoms, nuclear transition rates, neutron-nucleon scattering and rare kaon decays. These analyses depend on theoretical assumptions related to Higgs-nucleon coupling or hadronic contributions to kaon decays.

To summarize the situation in a slightly conservative tone: *a Higgs lighter than 5–6 GeV is very unlikely*, subject to mostly theoretical uncertainties, and massless and 1.2–100 MeV Higgs bosons had been probably excluded. A definite, unambiguous answer on light Higgs bosons (lighter than 5–6 GeV) was therefore an important mission of the LEP experiments. This is especially true if we consider some extension of the Standard Model. For heavier Higgs, LEP was unrivaled by any other experiments.

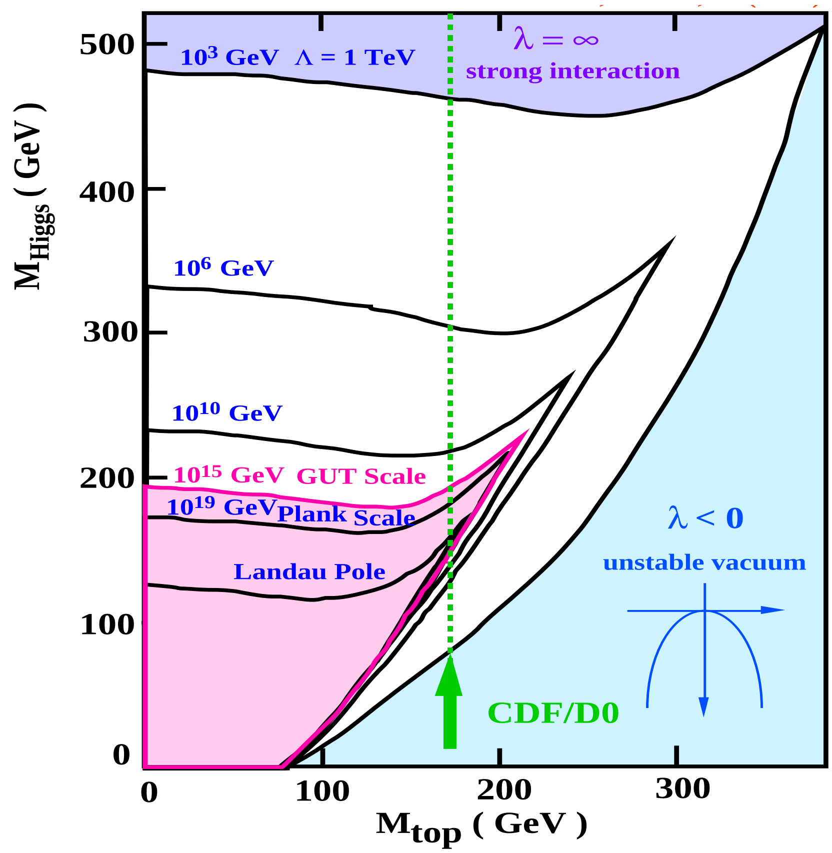


Figure 1: Allowed regions of the Standard Model Higgs as a function of the top quark mass.

Theoretical Bounds

Theoretically, within the Standard Model, the mass of the Higgs boson is just unpredictable. However, by considering the vacuum stability and the self-consistency at very high energy of the Standard Model, interesting bounds may be obtained.

The Standard Model Higgs mass m_H can be written as $m_H = \sqrt{2\lambda}v$, where λ is the quartic Higgs self-coupling. If the Higgs mass is too heavy, the coupling is too strong and may diverge at high energies. On the other hand, if it is too light, the coupling becomes negative and the vacuum may get unstable. So there is some theoretically allowed range of Higgs mass.

Allowed Higgs mass as a function of the top quark mass is plotted in Fig. 1.[7] There also exists a so-called Linde-Weinberg lower bound of about 10 GeV for smaller top quark masses ($<$ 80 GeV), which is not drawn in the Figure. At the time the top quark mass was not known, so that a very light Higgs was still considered to be possible if the top quark mass is around 80 GeV. Thus a discovery of light Higgs bosons ($<$ 5–10 GeV) at LEP could immediately indicate either the top quark mass is around 80 GeV or the Standard Model is wrong.

If the world is supersymmetric, then a different, important constraint applies. At the tree level, the lightest Higgs boson must be lighter than the Z^0 boson, which is kinematically within the eventual energy reach of the LEP machine. So it was expected that the LEP experiments would either discover a supersymmetric Higgs boson or exclude the TeV-scale supersymmetry. However, later in 1991 after the LEP had started its operation, theorists found radiative corrections would significantly loosen this constraint and the Higgs could be as heavy as 135 GeV, slightly beyond the reach of LEP.[8] So it was considered that there was a small chance that supersymmetry could still escape LEP's searches.

2 Higgs Searches at LEP

At LEP the Higgs boson can be produced via its coupling to the Z^0 boson. Because this coupling is the source of the heavy Z^0 mass, the production cross section is large and there is no ambiguity. While at LEP-I Higgs bosons are produced in the decays of Z^0, at LEP-II they are produced in association with Z^0 (Fig. 2).

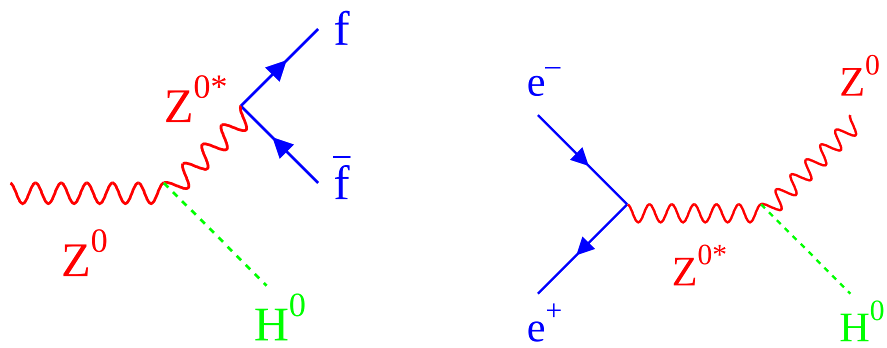


Figure 2: The Higgs boson production in the decays of Z^0 at LEP-I (left) and in the associated production with Z^0 at LEP-II (right).

Production of the Higgs boson that is almost as heavy as Z^0 is kinematically allowed at LEP-I. For Higgs bosons heavier than ≈ 55 GeV, however, the cross section becomes smaller than that of LEP-II (Fig. 3), and the signal-to-background ratio becomes hopeless. On the other hand, at LEP-II, the Higgs can be searched for up to the kinematical limit, that is, the mass close to the center-of-mass energy (with significant integrated luminosity) minus the Z^0 mass.

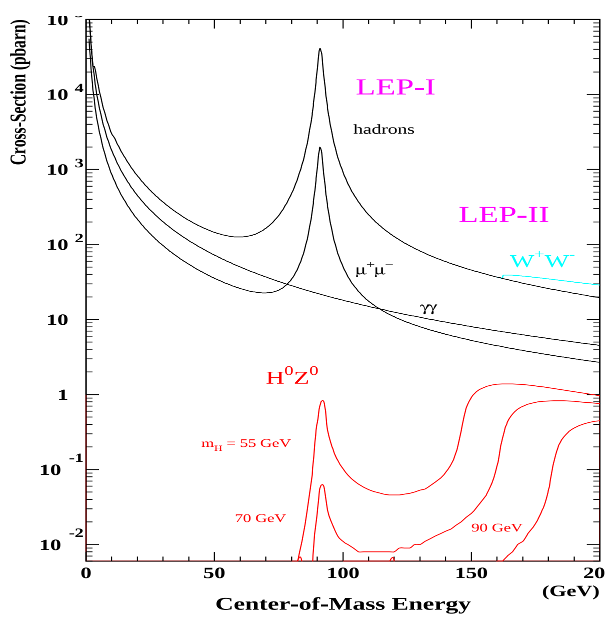


Figure 3: The Standard Model Higgs production cross sections for 55, 70 and 90 GeV are shown together with the various e^+e^- processes.

Figure 4 shows a history of the Higgs mass limits obtained by the OPAL experiment. It includes the preliminary results presented at various conferences in addition to the published results. It may be seen that the LEP-I mass limits saturated at 55–60 GeV towards the end of LEP-I running while the LEP-II limits rose up quickly to the (almost) kinematical limit of

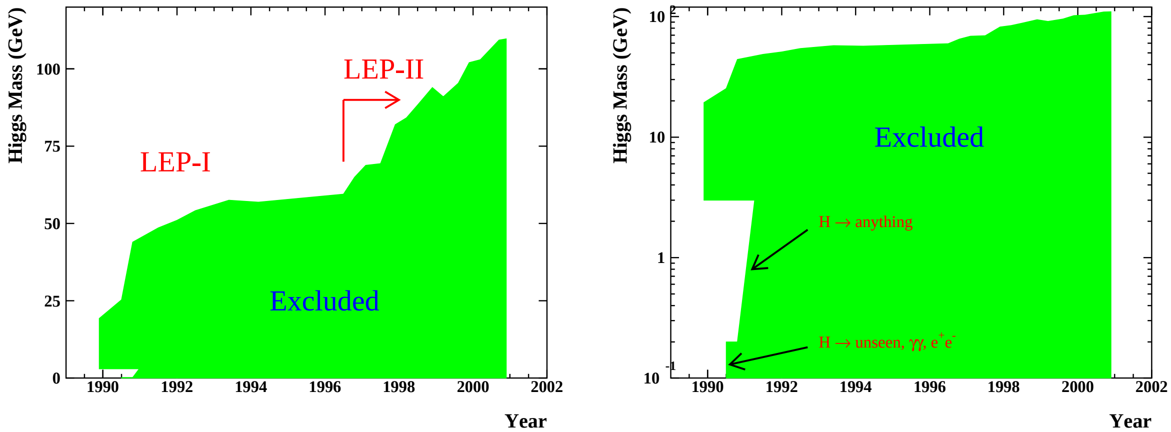


Figure 4: A history of the 95 % C.L. Higgs mass limits obtained by the OPAL experiment in a linear (left) and a logarithmic (right) scale of the Higgs mass.

113 GeV. Occasional small depressions indicate statistical fluctuations. Searches for light Higgs bosons that cannot decay into heavy quarks were carried out in separate analyses, because such Higgs bosons decay in quite different ways (Figure 4 (right)). Thus the Higgs searches at LEP can be categorized into the following 4 mass regions:

1. massless or almost massless Higgs ($0 \leq m_H < 2m_\mu$),

2. Higgs decaying to muons or light quarks ($2m_\mu \leq m_H < 2m_c$),

3. Higgs decaying to heavy quarks at LEP-I ($2m_c \leq m_H$), and

4. heavier Higgs at LEP-II ($m_H < \sqrt{s} - M_Z$).

In the following sections I will describe these searches in turn from zero mass up to the maximum accessible mass of ≈ 116 GeV.

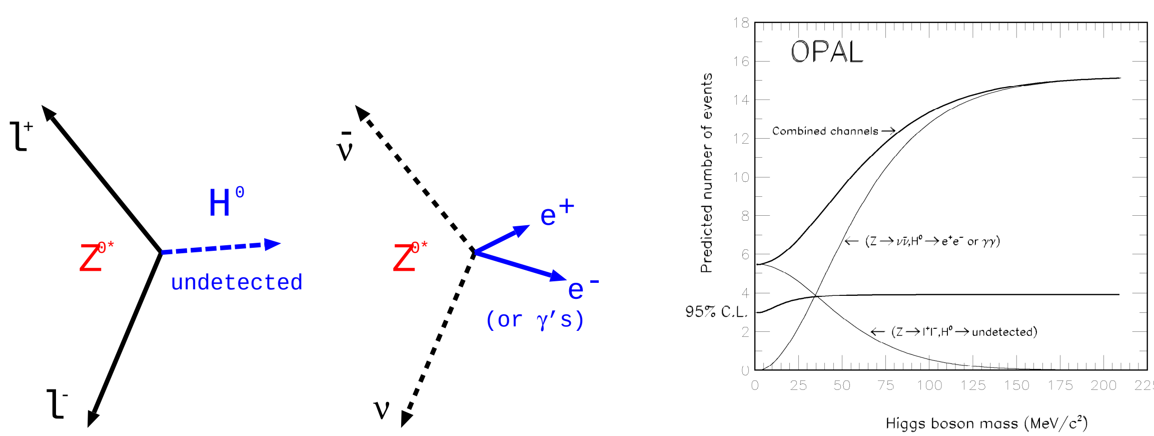


Figure 5: The searches for (almost) massless Higgs boson.

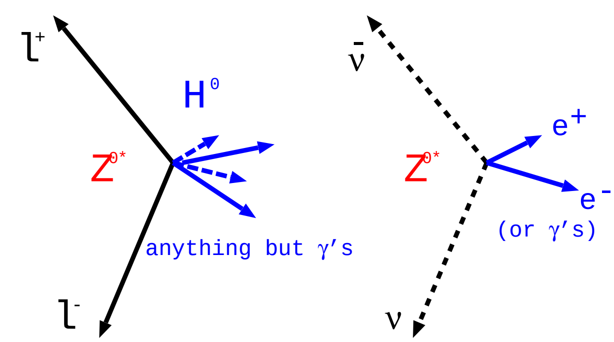
3 LEP–I

3.1 (Almost) Massless Higgs

For the mass region $0 \leq m_H < 2m_\mu$, the Higgs boson can only decay into gamma-rays and electrons, so that its life time may become very long, typically $c\tau > 1$ cm, and it may possibly escape the detector before decaying.

The OPAL experiment searched for two different event topologies[9]: (1) an acoplanar lepton (electron or muon) pair with missing energy/momentum taken by the undetected Higgs boson (Fig. 5 (left)), and (2) an electromagnetic mono-jet with no other detected particle (Fig. 5 (center)). The missing momentum taken by the massless Higgs in the event type (1) is about 9 GeV/c. While the former event type is sensitive to the massless Higgs and essentially background-free, the second event type is more sensitive to the heavier Higgs and has small irreducible background from $\nu\bar{\nu}\gamma$.

The result of the search was summarized in Fig. 5 (right); there was no evidence for the existence of the Higgs. As the cross section of the production of such light Higgs bosons is huge, only 1.2 pb^{-1} of data around the Z^0 peak was enough to exclude the Higgs boson with zero mass up to twice the muon mass.



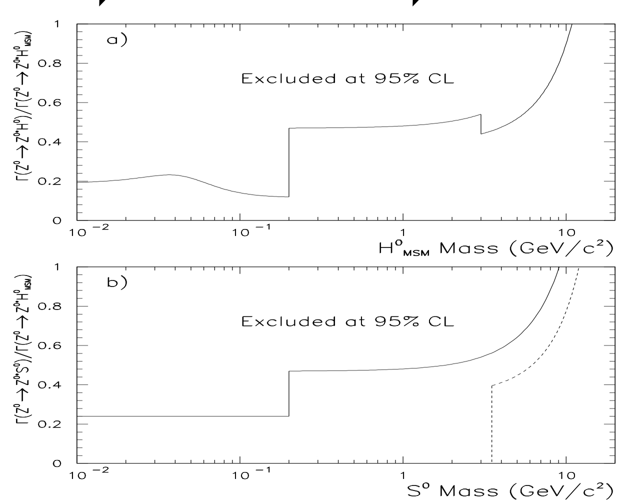


Figure 6: The result obtained from the decay independent search by the OPAL collaboration.

3.2 Higgs that Decays to Light Quarks

Most of the pre-LEP attempts to search for the Higgs was plagued with theoretical uncertainties related to the Higgs' couplings to light quarks and gluons, as described in Section 1. The Higgs bosons with the mass, $2m_\mu \leq m_H < 2m_c$, decay predominantly into light hadrons, and their branching ratios suffer from similar ambiguities.

Therefore the OPAL experiment made a special search for the Higgs bosons in this mass region, which did not rely on any assumption on the Higgs decay modes[10]. Two different event types were used:

1. an acoplanar lepton (electron or muon) pair plus anything, where 'anything' could be 'nothing' but not gamma rays (Fig. 6 (upper left));
2. an electromagnetic (i.e. electrons and/or gamma rays) mono-jet with missing energy and momentum (Fig. 6 (upper right)).

The dominant background for the type 1 was $\ell^+\ell^-\gamma$; this is why the gamma ray final states were not used in this type. The second event type covers the gamma ray final states and has the small background from $\nu\bar{\nu}\gamma$. These two event types together exhaust all possible final states.

The search excluded the Higgs in this mass region as indicated in Fig. 6 (lower (a)). The search was actually extended down to the zero mass and up to twice the b quark mass ($\approx$ 11 GeV). Since there was no assumption on the decay modes, this search result can be converted into limits on any new scalar particles that couples to the Z^0 boson (Fig. 6 (lower (b))).

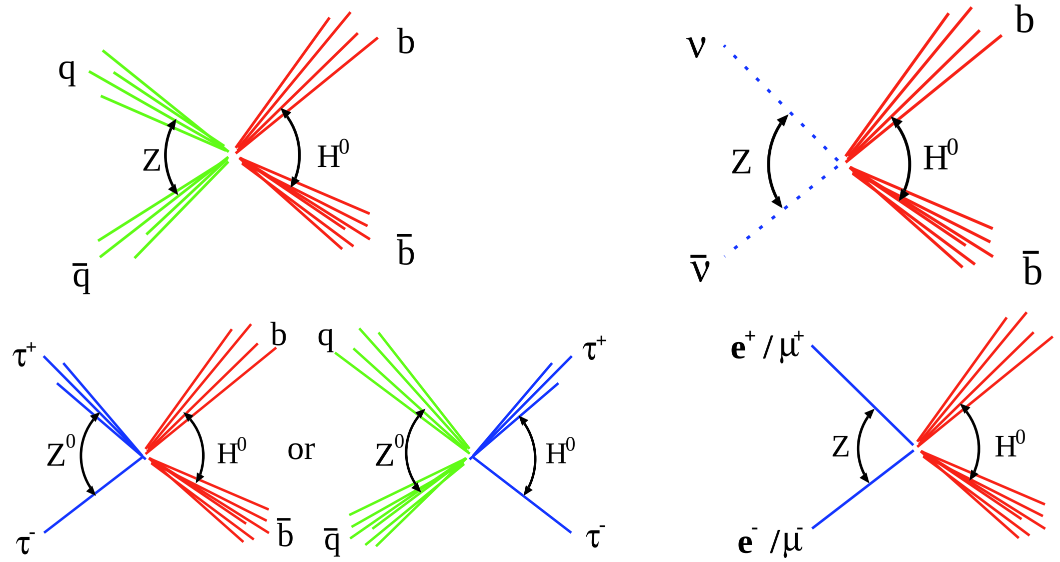


Figure 7: The four different topologies of the Higgs events for the Higgs that is heavier than twice the bottom quark mass. The four-jet channel (upper left), the neutrino or missing energy channel (upper right), the tau channel (lower left), and the lepton channel (lower right).

3.3 Higgs that Decays to Heavy Quarks at LEP-I

The Higgs bosons predominantly decay into heaviest possible fermions that are kinematically allowed, because their couplings are just proportional to the fermion masses. For $m_H = 20 \sim 60$ GeV, the decay $H \to q\bar{q}$ (almost always $b\bar{b}$) occurs ~ 94 % of the time and $H \to \tau\bar{\tau}$ at about 6 %. These predictions contain very small ambiguities thanks to the high masses involved.

Considering the Z^0 decay modes that were precisely measured at LEP, the final states of the Higgs production process $Hf\bar{f}$ are categorized into four topologies indicated in Fig. 7. Except for the four-jet channel $HZ^* \to b\bar{b}q\bar{q}$, that are plagued with abundant multi-jet background from the hadronic Z^0 decays, these events have quite distinct experimental signatures, and essentially background-free searches were possible. The main decay channels used in the searches are the neutrino channel (the branching ratio of ~ 19 %) and the lepton channel (the branching ratio of ~ 6.4 %). Typical search efficiencies for these channels were as high as 50 %.

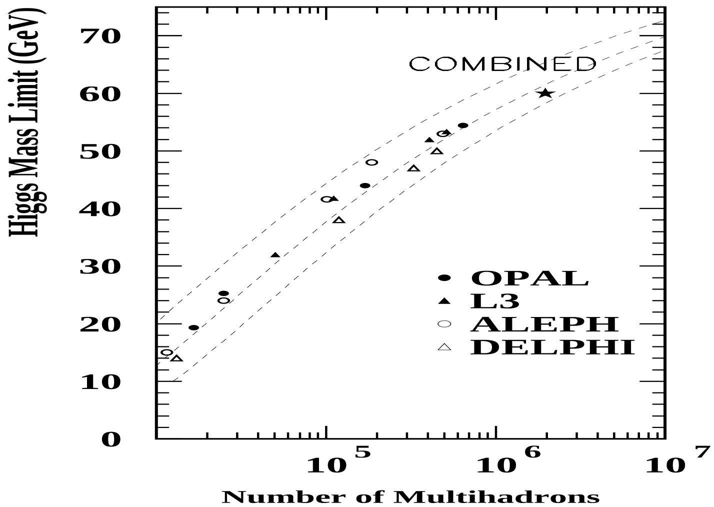


Figure 8: The Higgs mass limits as a function of the number of multi-hadronic events at LEP-I, as presented in the summer, 1992. The three lines shown are the expected limits for zero candidate and a fixed efficiency (100%, 50% and 30% respectively from above) in the two main channels.

Quite unfortunately the searches provided only the ever improving mass limits, but not the evidence of the Higgs boson. Shown in Fig. 8 are the history of the Higgs mass limit as a function of the number of hadronic Z^0 decays.[11] It is seen that the mass limit had been increasing just as expected for background-free searches.

Towards the end of the LEP-I run, however, background events were starting to appear. For the neutrino channel, the background mainly arises from (1) hadronic Z^0 decays where heavy quarks decayed into neutrinos which carried away a large amount of energy, or (2) some isolated energetic particles escaped into the dead areas of the experiment. By August 1995, three such events were found for 13 million hadronic Z^0 decays accumulated by the four LEP experiments,[12] but the estimated mass was all lower than 40 GeV that had been already excluded. These extremely rare events were hard to estimate. For the lepton channel, there is a physics background from four-fermion final states, $Z^*\gamma^* \to f\bar{f}f'\bar{f}'$. This background has a similar cross section to the ~ 60 GeV Higgs boson. Altogether a total of 9 events above 40 GeV were found. Fortunately the hypothetical Higgs mass can be precisely estimated with a resolution of about 1 GeV, and no accumulation of events at any fixed mass was observed.

The LEP combined limit had reached 65.2 GeV by August 1995,[12] and the LEP machine finally started to leave the Z^0 resonance later in the same year. We now turn to the searches at LEP-II.

4 LEP–II

The precision electroweak measurements at LEP–I indicated the top quark is as heavy as 175 GeV,[13] and that was exactly where the Tevatron experiments discovered the top quark in 1995. Taking a look back at Fig. 1, it turned out, for such a heavy top quark, it was quite natural that the Higgs boson was not discovered at LEP-I. Fig. 1 also indicates that, if we assume the grand unification at around 10^{15} GeV, there would be no hope for a Higgs discovery at LEP-II either. But such a simple GUT scheme was excluded by the proton decay experiments, and the gauge couplings measured precisely at LEP-I indicated we need supersymmetry to grand unify the gauge interactions.

Supersymmetry, a new physics below the TeV energy region, requires a Higgs boson to be lighter than $\sim$ 135 GeV. This is consistent with the precision electroweak data, including the directly measured top quark mass, which provided the upper bound of the Higgs mass of about 200 GeV.[13] Thus there had been always high expectations for the LEP-II searches for the Higgs.

At LEP-II the Higgs boson could be produced in association with the Z^0 boson. Thus the Higgs bosons as heavy as the maximum center-of-mass energy minus the Z^0 mass (that is, roughly $207 - 91 = 116$ GeV) could be produced at LEP-II. Although the final state topologies are the same as at LEP-I (Fig. 7), the LEP-II searches suffer from much higher background rates due to the four-fermion final states such as WW or ZZ processes, in contrast to LEP-I. However the four-jet channel that has a highest branching ratio of about 50% can also be used in the searches at LEP-II, thanks to the additional kinematical constraints.

To fight against the large background at LEP-II, mainly $q\bar{q}$ pair production with (multiple) gluon radiation, WW, and ZZ processes, we utilized the following tools:

- b-tagging, i.e. the requirement of b quark in the hadronic final state;
- the kinematical reconstruction of the mass of the hypothetical Higgs boson; and
- Higgs probability analysis.

In the following sections, after explaining these three important analysis tools, the final LEP searches for the Higgs bosons in the year 2000 are described to some details, and the final LEP result is summarized in the end.

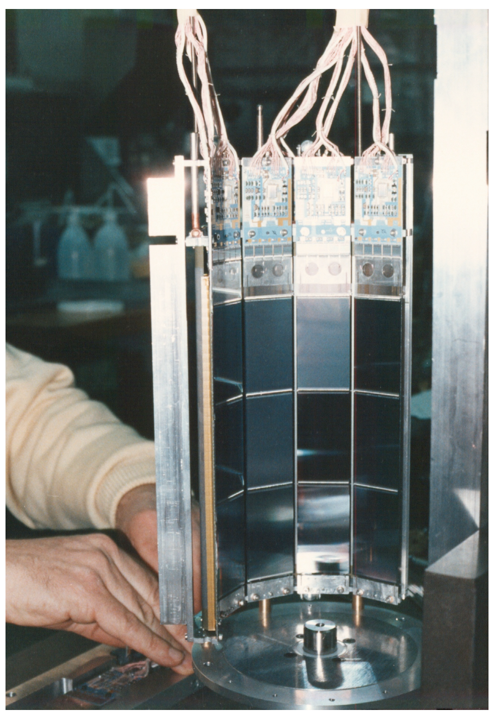


Figure 9: Part of the OPAL Si vertex detector.

4.1 B-Tagging

The most important handle to identify b quarks in the hadronic final state is the long lifetime of the b hadrons. The b hadrons typically travel several mm before they decay into lighter hadrons at LEP energies. Thus, by finding these decay vertices with the help of the high resolution Si micro vertex detector (Fig. 9), b quark production is identified with high efficiency. To distinguish c hadrons which also travel some distance before decaying, the multiplicity of the tracks coming out of the vertices, the impact parameters of these tracks, and/or the so-called "vertex mass" are utilized. To make the best of these discriminating variables, either likelihood selections or neural network algorithms are applied. Almost all background from WW are discarded this way.

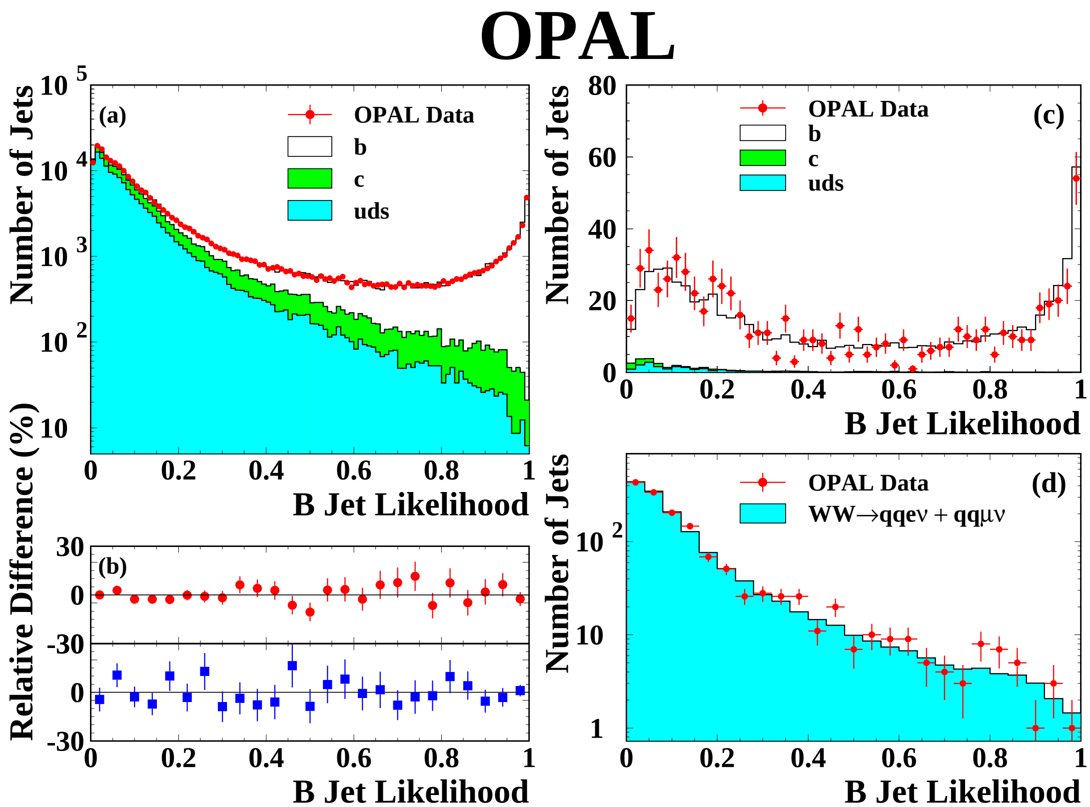


Figure 10: An example of the b-tag performance/modeling checks. (a) and (b) show the comparison between data and MC simulations. (c) B-tagging over the $b\bar{b}$ sample taken at the Z^0 peak. (d) The semi-leptonic WW sample that should contain no b jet.

The performance of the b quark tagging was carefully checked by using $Z \rightarrow q\bar{q}$ taken at the Z^0 peak and $WW \rightarrow \ell\nu q\bar{q}$. By applying the b-tag algorithm to one of the jets in the $Z \rightarrow q\bar{q}$ events, a sample of pure b quark jets was obtained. Also $WW \rightarrow \ell\nu q\bar{q}$ serves as a sample that does not contain b quarks. An example of the b-tag performance / MC modeling checks using these control samples is shown in Fig. 10.

4.2 Mass Reconstruction

Even after the powerful b-tag selection, there are much more background events, mainly from ZZ and multi-jet $Z \rightarrow q\bar{q}$ events, than possible Higgs signals. Then to discriminate the signal further, the mass of the hypothetical Higgs is reconstructed from the kinematics of the event. The width of the Higgs boson is in the order of tens of MeV for the mass of interest and is negligible compared to the measurement resolutions. Therefore the Higgs signal should appear as a peak in the reconstructed mass distribution.

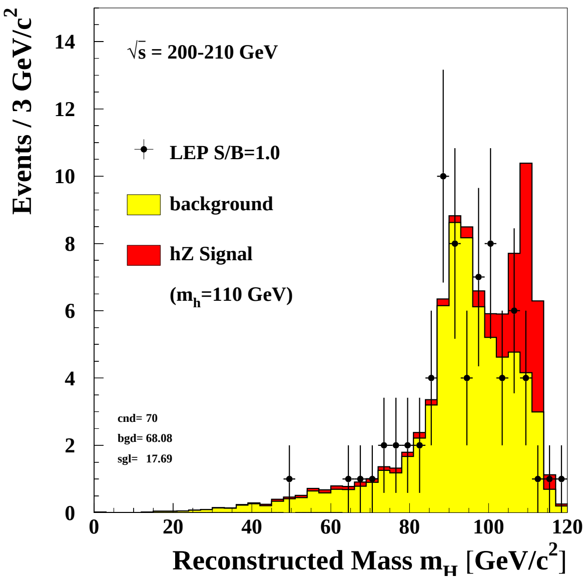


Figure 11: An example of distributions of the reconstructed Higgs mass. All the data at highest energies collected by July 2000 were combined. The simulated signal of the 110 GeV Higgs is shown as a red histogram.

The kinematical mass reconstruction is tested using the WW events and its resolution and possible bias are checked. The reconstructed mass resolution is typically 2–5 GeV for each event (about 3.5 GeV if averaged over the final states and experiments).

An example of the mass distributions obtained from the analyses using all the data at highest energies collected by July 2000 are shown in Fig. 11.[14] It is seen that the Higgs boson with the mass of 110 GeV may be comfortably excluded.

However, for heavier Higgs bosons barely produced at the threshold, the life is much harder. To make the best of the LEP data and to draw some conclusion on the heaviest possible Higgs boson, we now turn to a probability analysis that uses "Higgs likelihood" of each Higgs candidate event.

4.3 Higgs Probability Analysis

Because there are some background events left out, and the statistics is always low for the Higgs mass region of interest, some sort of statistical analysis which utilizes best out of the available information has to be made.

Each LEP experiment utilized a likelihood analysis or an artificial neural network to make a final selection of candidate events. The output of the likelihood analysis or the neural network, which we denote as $\mathcal{G}$, provides a good discriminating variable for each candidate event. The variable $\mathcal{G}$ serves as a "Higgs likelihood" and reflects particularly the result of the b-tagging of the event.

In the two dimensional distributions of $\mathcal{G}$ and the reconstructed mass for all the selected candidate events, a binned likelihood analysis was made. Two likelihood values were then obtained: A likelihood $\mathcal{L}_b$ that the data are all background processes, and a likelihood $\mathcal{L}_{s+b}(m_H)$ that the data are a combination of the Higgs signal and the background for a given value of the Higgs mass, m_H. Then the likelihood ratio $Q \equiv \mathcal{L}_{s+b}/\mathcal{L}_b$ provides a good indicator of possible Higgs signal. For convenience, we use the quantity $-2\ln Q$, which, in the limit of high statistics, corresponds to the χ^2 difference between the signal+background and the background-

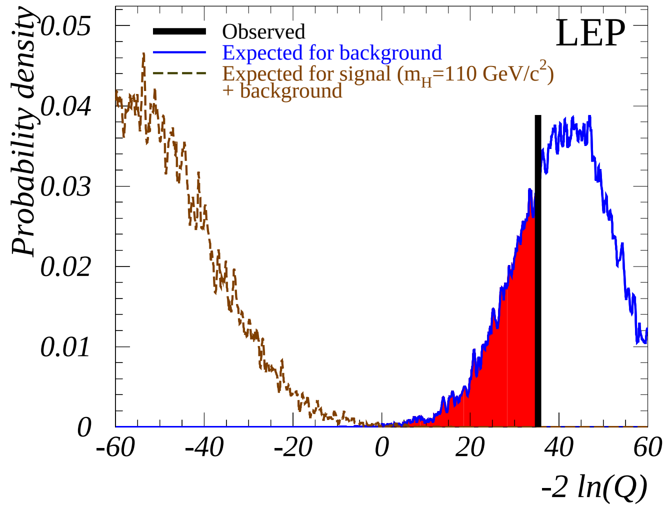


Figure 12: The distributions of $-2\ln Q$ for the background (the right distribution) and the signal + background for the 110 GeV Higgs production (left) for all the available LEP data. The observed value is indicated by the vertical line. The background probability is the red area of the background distribution integrated to the left of the vertical line.

only hypotheses; Especially it becomes negative if there is a Higgs signal.

An example of the distributions of $-2\ln Q$ are shown for all the available LEP data in Fig. 12, where the distributions for the background-only and for the background plus the 110 GeV Higgs signal are clearly separated. The observed value of $-2\ln Q$, indicated by the vertical line, is perfectly compatible with the background-only distribution and disagree sharply with the background plus signal distribution. The 100 GeV Higgs bosons are therefore clearly excluded. The probability that the observation is consistent with the background hypothesis may be given by the red area of the background distribution integrated to the left of the vertical line.

4.4 The Year 2000 — Possible Signal

Toward the end of 1999, the LEP machine reached the collision energy of 202 GeV, much higher than one had initially expected. During the winter shutdown in 1999–2000, the superconducting cavities were conditioned and some of the LEP–I normal copper cavities were placed back to help boost the collision energy further. To go beyond what was thought to be the maximum achievable energy, various techniques were also tried: For example, the correction magnets were used to enlarge the bending radius and the RF frequency was lowered to make the beam trajectory a bit larger so that the synchrotron radiation should be suppressed.

Because of the klystron trips, an operation at the highest energy risks the running efficiency and therefore the total integrated luminosity. To secure a high running efficiency, a new operation scheme was adopted for the running in 2000. In the new “mini ramp” scheme, the beams are first accelerated to a slightly lower energy, and, as the beam intensity decreases, they are ramped up in a few steps to the maximum energy. This scheme leaves a good safety margin in the total klystron power during each step of the operation while still providing reasonably good luminosity at the highest energies.

The LEP physics run started in April, and immediately after running at the Z^0 peak for detector calibration, LEP successfully started a stable operation at 205 GeV. Later it reached the maximum possible collision energy of 209 GeV. The total integrated luminosity taken at energies larger than 206 GeV ($= M_Z + 115$ GeV) was 536 pb^{-1} for the four LEP experiments.

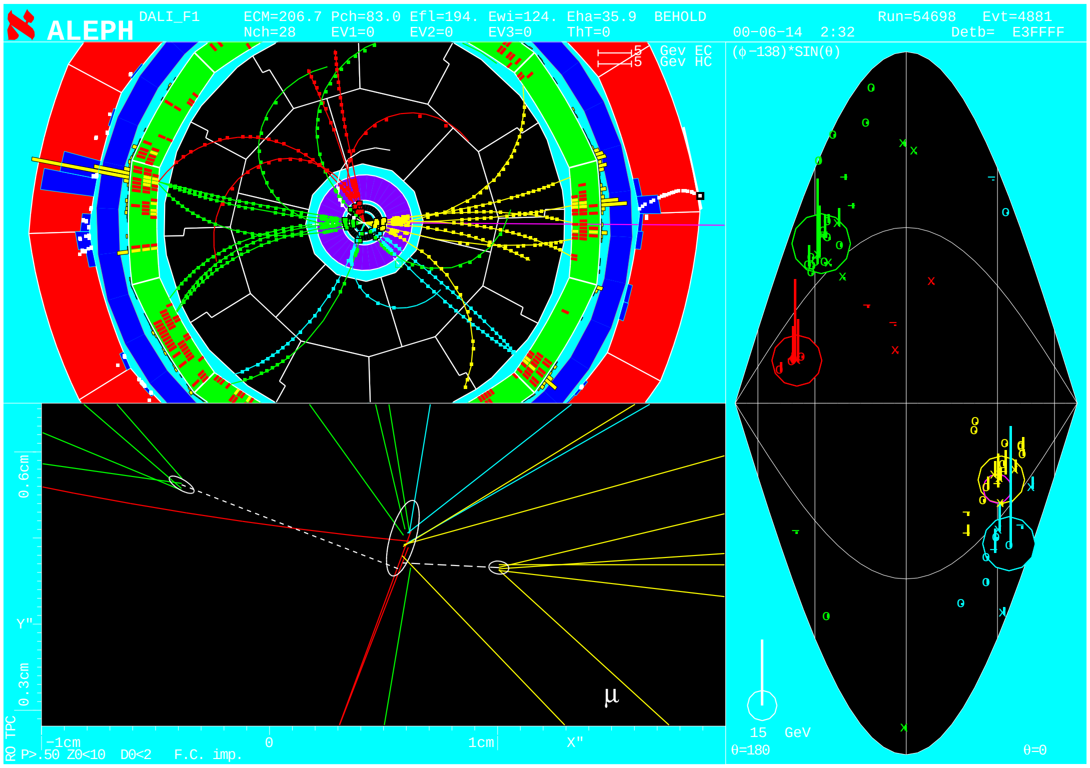


Figure 13: One of the most significant ALEPH Higgs candidate event.

Including the data in the previous year, the integrated luminosity above 189 GeV, corresponding to the data sample used in the final combination in this note, was 2461 pb^{-1}.

At the LEP Committee Meeting on September 5, 2000, the ALEPH Collaboration reported an excess of events that suggested the production of the Standard Model Higgs boson with the mass of about 115 GeV,[15] while the other three experiments did not observe any excess. One of the ALEPH Higgs candidate event is shown in Fig. 13. In fact the ALEPH excess was a bit too large for the SM Higgs boson but would be consistent if combined with the null results of the other experiments. The probability for the background to produce such an excess was estimated to be 2.5%.

It was then decided that the LEP shutdown scheduled at the end of September was postponed by one month to clarify this ambiguous situation. The LEP machine had continued its operation until November 2. The bulk of the new data were quickly analyzed and the preliminary results were presented at the LEP Committee on November 3[16]. The significance of the ALEPH excess was slightly degraded, but the L3 collaboration observed an excess of events, especially a candidate in the missing energy final state ($\mathrm{H}\nu\bar{\nu}$), compatible with a 115 GeV SM Higgs boson[17]. Together with the "null" results of the other two experiments, DELPHI and OPAL, the overall excess at 115 GeV was estimated to be a 2.9σ deviation from the background (i.e. the background probability of 0.4%). See Table 2 below. The results of ALEPH, DELPHI, and OPAL were later published by including all data after a thorough revision of the analysis procedures[18].

As it appeared that the significance of the excess had grown according to the data statistics, the LEP experiments requested for running in 2001 to determine definitely whether it is a statistical fluctuation or a discovery[16]. It was thought that, with an additional module of superconducting cavities available, LEP should be able to run at slightly higher energies in 2001, and therefore a four-to-six-month running would be enough to put a definite end to the controversy.

On November 8, however, the CERN Management decided that the data was not sufficiently conclusive to justify running LEP in 2001, and that CERN should proceed full-speed ahead with the Large Hadron Collider project.

After the final results by the four LEP collaborations became available,[19] they were combined and presented at the 31st International Conference on High Energy Physics, Amsterdam in July, 2002.[20] This combination of all the final results are briefly summarized below.

4.5 The Final Result

In Table 1 the properties of the 10 most significant candidate events are listed, where the last column lists "weights" of the events for $m_H = 115$ GeV.[a] From this table it may be seen that the excess concentrates mainly in the four-jet final state and in the ALEPH data.

	Expt	E_{CM}	Type	M_{rec}	Weight
1	Aleph	206.6	4-jet	114.1	1.76
2	Aleph	206.6	4-jet	114.4	1.44
3	Aleph	206.4	4-jet	109.9	0.59
4	L3	206.4	E-miss	115.0	0.53
5	Aleph	205.1	Lepton	117.3	0.49
6	Aleph	206.5	Tau	115.2	0.45
7	Opal	206.4	4-jet	108.2	0.43
8	Aleph	206.4	4-jet	114.4	0.41
9	L3	206.4	4-jet	108.3	0.30
10	Delphi	206.6	4-jet	110.7	0.28

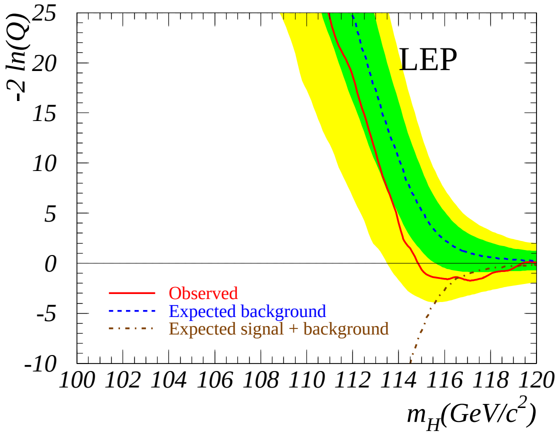
Table 1: The ten most significant candidates. M_{rec} is the reconstructed mass.

The value of $-2\ln Q$ as a function of the assumed Higgs mass is shown in Fig. 14 (left). It becomes negative around $m_H = 115$ –118 GeV and is compatible with the signal+background hypothesis. In Fig. 14 (right) the expected distributions of $-2\ln Q$ for the assumed Higgs mass of 116 GeV are plotted. The separation between the distribution of the background and that of the Higgs production indicates the rather poor statistical power of the LEP data for the 116 GeV Higgs boson. The observed value is indicated by the vertical line and is slightly negative. The "background" probability that the background fluctuates to give the value of $-2\ln Q$ equal to or lower than the observed one will give a degree of compatibility with the background hypothesis. It is given by the red area of the background distribution integrated to the left of the vertical line, which is 9.9%. Averaged in the vicinity of 116 GeV, the background probability is about 8%, corresponding to 1.7σ deviations from the background hypothesis in a "one-sided Gaussian" convention. On the other hand the signal+background probability, the blue area in Fig. 14 (right), is 37%. The background probabilities of the individual experiments are listed in Table 2.

Thus the observed excess of events, seen mostly in the ALEPH data and in the four-jet channel, is compatible with the 116 GeV Higgs boson with a 37% probability, but is also consistent with the background fluctuations with a 8% probability.

A lower bound for the SM Higgs boson mass can be derived from these probability density distributions. It was 114.4 GeV at the 95% confidence level while a lower bound as good as 115.3 GeV was expected from the statistics.

[a] A weight of each event is defined in such a way that it contributes linearly to the log likelihood ratio, $-2\ln Q$.



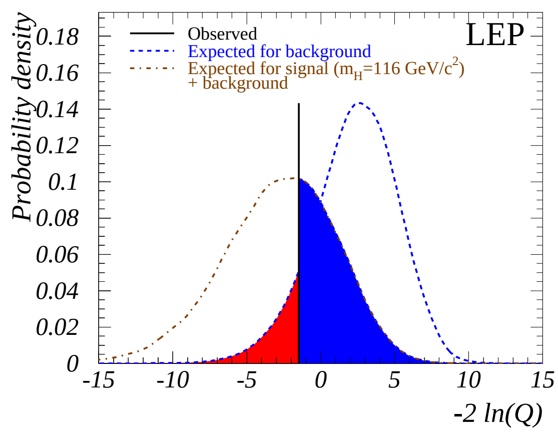


Figure 14: *Left:* The observed values of $-2\ln Q$ as a function of the hypothetical Higgs mass m_H (the solid red line). The shaded bands are the regions within 68% and 95% probability for the background-only case. *Right:* The probability density distributions of $-2\ln Q$ for the background (the right distribution) and for the 116 GeV Higgs production (left). The observed value is indicated by the vertical line.

	ALEPH	DELPHI	L3	OPAL	LEP
Nov 2000	6.5×10^{-4}	0.68	0.068	0.19	4.2×10^{-3}
Final	2.4×10^{-3}	0.87	0.35	0.54	0.099
Mass limit (GeV)	111.5	114.3	112.0	112.8	114.4

Table 2: The background probabilities presented in November 2000 and those published later. The obtained 95% C.L. mass limits and the combined results are also shown.

5 Conclusion

The searches for the Standard Model Higgs bosons by the LEP experiments were a real success and significantly exceeded the early expectations. Combining all the LEP data, all the mass region from zero mass up to 114.4 GeV was definitely excluded. A possible excess of events observed slightly above this mass limit could be interpreted as production of the Higgs boson but is also compatible with the background at the 8% level.

Together with the electroweak data, the Standard Model Higgs boson must exist somewhere between 114.4 GeV and 193 GeV.[13] If the universe is supersymmetric, as suggested by the unification of three gauge couplings, the lightest Higgs boson must lie in a very narrow energy region up to $\sim$ 135 GeV. This sneaking particle will certainly be the subject of detailed studies by the next generation collider experiments at the Large Hadron Collider and at the Linear Collider.

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