Searches for Higgs Bosons in the Standard Model and in the Minimal Supersymmetric Standard Model at LEP

P. Igo-Kemenes[a]
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[a]Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany

In twelve years of successful operation, the e^+e^- collider LEP and the associated experiments have extended the sensitivity of Higgs boson searches over a large mass range. The current status of the search results is presented, concentrating on Higgs bosons in the Standard Model and in the Minimal Supersymmetric Standard Model.

1. Introduction

One of the main challenges in high-energy particle physics is the discovery of Higgs bosons. Their existence is related to the generation of elementary particle masses which can be introduced in gauge theories by the Higgs mechanism. In the Standard model (SM) and its extensions, fundamental scalar "Higgs" fields interact with each other such that they acquire non-zero vacuum expectation values, and the gauge bosons and fermions obtain their masses by interacting with the vacuum Higgs fields. Associated with this mechanism is the existence of massive scalar particles, Higgs bosons.

The SM requires one Higgs field doublet and predicts a single neutral Higgs boson, H^0. Beyond the SM, supersymmetric (SUSY) models are of interest since they provide a consistent framework for the unification of the gauge interactions at a high energy scale $\Lambda_{GUT} \approx 10^{16}$ GeV and an explanation for the stability of the electroweak energy scale in the presence of quantum corrections (the "scale hierarchy problem"). Moreover, their predictions are compatible with existing high-precision data. The Minimal Supersymmetric Standard Model (MSSM) uses two Higgs field doublets and predicts the existence of three neutral and a pair of charged Higgs bosons. While in the SM the mass of the Higgs boson is not predicted, in SUSY models the Higgs masses are related to the gauge couplings. As a consequence, one of the neutral Higgs bosons, h^0, must have its mass close to the electroweak energy scale: less than M_Z at the tree level and, in the MSSM, not exceeding 130 GeV when radiative corrections are taken into account. Searches for h^0 at LEP are thereby highly motivated.

The Higgs phenomenology is thoroughly discussed in Ref. [1]. Prior to LEP, Higgs searches were only sensitive to masses below a few GeV. The LEP collider, operating for five years at a centre-of-mass energy $\sqrt{s} \approx M_Z$ (the LEP1 phase) definitively excluded a SM Higgs boson with mass between zero and about 65 GeV. Since 1995, the centre-of-mass energy has increased each year (the LEP2 phase), reaching $\sqrt{s}$=208 GeV before the final shutdown in Nov. 2000. The combined data of the four experiments, ALEPH, DELPHI, L3 and OPAL, have extended the range of sensitivity of the searches up to the kinematic limit of the principal production processes, $e^+e^- \rightarrow H^0Z^0$ and h^0Z^0, that is $(\sqrt{s})_{max} - M_Z \approx$ 117 GeV.

2. Constraints on Higgs masses

In the SM, the Higgs mass $m_{H^0} = \sqrt{2\lambda}\, v$ is proportional to the vacuum expectation value v of the Higgs field, which is fixed by the Fermi coupling. The quartic Higgs coupling λ is not determined, but arguments of self-consistency of the SM can be used to place upper and lower bounds on the mass.

Since the running coupling λ rises with energy, the theory would eventually become non-perturbative. The requirement that this does not occur at a scale lower than Λ defines an upper bound for the Higgs mass. A lower bound is obtained from top-loop induced quantum corrections to the Higgs interaction potential. The requirement that the electroweak minimum is an absolute minimum up to a scale Λ yields a "vacuum stability" condition which limits m_{H^0} from below. These theoretical bounds are summarised

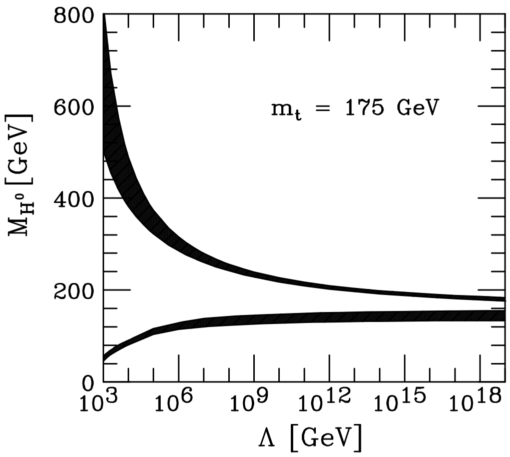

Figure 1. *Bounds on the Higgs mass based on arguments of self-consistency of the SM [2]. Λ denotes the energy scale at which the SM would become non-perturbative or the electroweak potential unstable. The dark bands represent theoretical uncertainties.*

in Figure 1. If the SM is to be self-consistent up to $\Lambda = \Lambda_{GUT}$, there remains only a narrow band from about 130 to 190 GeV for the mass. Since such masses are beyond reach at LEP2, the discovery at LEP would have indicated the onset of new physics below Λ_{GUT}.

Indirect experimental bounds are obtained from fits to precision measurements of electroweak observables, primarily from Z^0 decay data, and to the measured top and $\mathrm{W}^{\pm}$ masses. These measurements are sensitive to $\log(m_{\mathrm{H}^0})$ through radiative corrections. Figure 2 shows the χ^2 of the fit as a function of m_{H^0}. Currently the

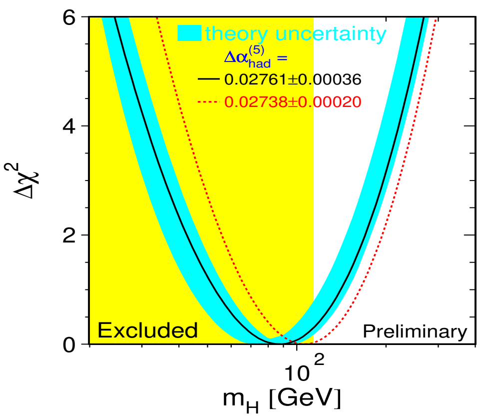

Figure 2. *The χ^2 of the fit to the high-precision electroweak data from LEP and SLC, and measurements of the top and $\mathrm{W}^{\pm}$ mass at the Tevatron.*

best fit value is $m_{\mathrm{H}^0}{=}88^{+53}_{-35}$ GeV or $m_{\mathrm{H}^0}{<}196$ (95% c.l.) [3], still consistent with the SM being valid up to the GUT scale.

The MSSM is a model with two Higgs field doublets (2HDM) of "type II" where one field, with v.e.v. v_1, couples to "down" quarks and charged leptons while the second, with v.e.v. v_2, couples to "up" quarks only. Assuming CP invariance [4], the spectrum of physical Higgs bosons consists of two CP-even neutral scalars h^0 and H^0 (h^0 is defined to be the lighter one), one CP-odd neutral scalar A^0, and one pair of charged Higgs bosons $\mathrm{H}^{\pm}$.

At tree level, only two parameters are required to fix all Higgs masses and couplings. A convenient choice is the ratio $\tan\beta{=}v_2/v_1$ and the mass m_{A^0} of the CP-odd scalar A^0. Often the mixing angle α is used which diagonalises the CP-even Higgs mass matrix; α can also be expressed in terms of $\tan\beta$ and m_{A^0}. The following ordering of masses is valid at the tree level: $m_{\mathrm{h}^0}{<}M_{\mathrm{Z}}$ and m_{A^0}; $m_{\mathrm{A}^0}{<}m_{\mathrm{H}^0}$, and $M_{\mathrm{W}}{<}m_{\mathrm{H}^{\pm}}$. These relations are modified by radiative corrections due to incomplete cancellation between virtual top and scalar-top (stop) loops [5] which principally affects the masses and decays in the neutral Higgs sector. These depend strongly on the top and stop masses, on soft SUSY breaking parameters, and on the mixing between the SUSY partners of the left- and right-handed top quarks (stop mixing).

3. Higgs boson production and decay

The principal mechanism for producing the SM Higgs particle in e^+e^- collisions at LEP energies is Higgs-strahlung in the s-channel, $e^+e^- \rightarrow H^0Z^0$. The Z^0 boson in the final state is either virtual (LEP1) or on mass shell (LEP2). The cross-section, σ_{SM}, is shown in Figure 3 as a function of $\sqrt{s}$, together with that of other SM processes which constitute the main background. The production by W^+W^- fusion in the t-channel, $e^+e^- \rightarrow \bar{\nu}_e\nu_e H^0$, has a small contribution at LEP energies.

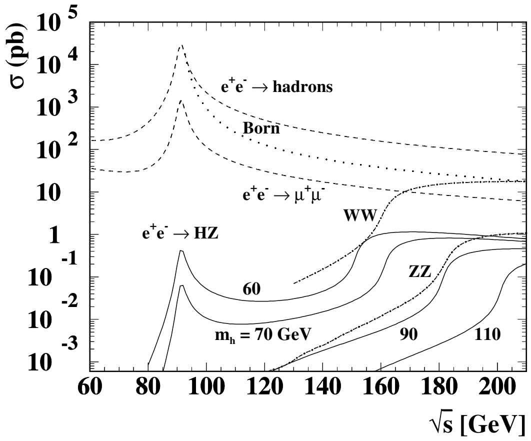

Figure 3. *Cross-sections as a function of $\sqrt{s}$ for Higgs-strahlung in the SM with fixed values of m_{H^0} (full lines), and for other SM processes which contribute to the background.*

In the 2HDM, of which the MSSM is a particular model with supersymmetry, the main production processes at LEP energies are Higgs-strahlung, $e^+e^- \rightarrow h^0Z^0$, and pair production, $e^+e^- \rightarrow h^0A^0$. Fusion processes play a marginal role at LEP. In the MSSM the heavier neutral CP-even Higgs boson H^0, and also $H^{\pm}$, are confined to masses barely accessible at LEP. The cross-sections for Higgs-strahlung and pair production are related to the SM cross-section σ_{SM} by the angles α and β which were introduced before.

$$\sigma(e^+e^- \rightarrow Z^0h^0) = \sin^2(\beta - \alpha)\sigma_{SM}$$

$$\sigma(e^+e^- \rightarrow A^0h^0) = \cos^2(\beta - \alpha)\bar{\lambda}\sigma_{SM}$$

($\bar{\lambda}$ is a kinematic phase-space factor). These cross-sections are complementary due to the factors $\sin^2(\beta - \alpha)$ and $\cos^2(\beta - \alpha)$. In the MSSM, $e^+e^- \rightarrow h^0Z^0$ has the larger cross-section at small $\tan\beta$ while at large $\tan\beta$ it is $e^+e^- \rightarrow h^0A^0$, unless the latter is suppressed kinematically.

For masses of interest at LEP, the SM Higgs boson decays preferentially to fermion anti-fermion pairs, of which $H^0 \rightarrow b\bar{b}$ has the largest branching ratio (for $m_{H^0} > 2m_b \approx 10$ GeV) since the Yukawa coupling $H^0 f\bar{f}$ is proportional to m_f. Decays to $\tau^+\tau^-$, $c\bar{c}$ and gluon pairs (via loops) are below 10%. The decay width is less than 10 MeV.

In the *2HDM* (and thus in the MSSM), the couplings to "up" and "down" fermions are modified with respect to the SM couplings by factors which are summarised in Table 1.

	"up"	"down"
SM-Higgs:	1	1
2HDM h^0:	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
H^0:	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
A^0:	$1/\tan\beta$	$\tan\beta$

Table 1
Factors relating the SM Higgs couplings to the corresponding couplings in the 2HDM (tree level).

4. The LEP search environment

At LEP1, the four experiments analysed over 17 million Z^0 decays. They set lower bounds of about 65 GeV for the mass of the SM Higgs boson and of about 45 GeV for the masses of h^0, A^0 (valid for $\tan\beta>1$), and $H^\pm$ bosons. Substantial data samples have also been collected at LEP2 energies including more than 40,000 $e^+e^-\to W^+W^-$ events.

The search enviroment is quite different in the two LEP phases. The signal-to-background ratio is more favourable at LEP2 (see Figure 3) despite the additional backgrounds from $e^+e^-\to W^+W^-$ and Z^0Z^0. The latter processes have kinematic properties similar to the signal, especially for $m_{H^0}\sim M_W$, M_Z, but since at LEP2 the Z^0 boson is on the mass shell, constrained kinematic fits yield sufficient separation. Furthermore, the four collaborations have considerably upgraded their b-tagging hardware and software for LEP2. Jets with b-flavour (e.g. from Higgs decays) are recognised by secondary decay vertices or tracks with large impact parameters, identified by means of high-precision silicon-microvertex detectors. Other useful indicators for b-flavour are high-p_T leptons from $b\to c\ell^-\bar{\nu}_\ell$ decays ($\ell = e, \mu$) and several jet properties which are all combined using likelihood or neural network techniques.

The following final states provide good sensitivity for neutral Higgs bosons (here h^0 may designate either the SM Higgs boson or the lightest CP-even neutral scalar in the MSSM).

(a) The most abundant *four-jet* topology is produced by the $(h^0\to b\bar{b})(Z^0\to q\bar{q})$ and $(h^0\to b\bar{b})(A^0\to b\bar{b})$ final states. In the SM it occurs with a branching ratio of about 60%. In the first process, the invariant mass of two jets is close to M_Z, while the other two jets contain b-flavour. In the second process, the Z^0 mass constraint cannot be used, but b-flavour is expected in all four jets. The Higgs mass can be reconstructed with a typical resolution of 2.5 GeV.

(b) The *missing energy* topology is produced mainly by the $(h^0\to b\bar{b})(Z^0\to\nu\bar{\nu})$ final state. In the SM it has a branching ratio of about 17%. The signal has two b-jets, substantial missing transverse momentum and missing mass compatible with M_Z. The reconstruction of the Higgs mass is achieved with a typical "central" resolution of 3 GeV but the distribution has pronounced tails. A similar event topology also occurs in h^0Z^0 and h^0A^0 if the Higgs bosons decay into "invisible" SUSY particles (e.g., neutralinos), or in the W^+W^- fusion process leading to $b\bar{b}\nu_e\bar{\nu}_e$.

(c) In the *leptonic final states* $(h^0\to b\bar{b})(Z^0\to e^+e^-,\ \mu^+\mu^-)$ the two leptons reconstruct to M_Z and the two jets have b-flavour. Although the branching ratio is small (only about 6% in total), this channel adds to the overall search sensitivity because it has low background and good mass resolution, typically 1.5 GeV, if m_{h^0} is taken to be the mass recoiling against the reconstructed Z^0 boson.

(d) The *tau final states* are produced in the SM and MSSM processes $(h^0\to\tau^+\tau^-)(Z^0\to q\bar{q})$, $(h^0\to q\bar{q})(Z^0\to\tau^+\tau^-)$, $(h^0\to\tau^+\tau^-)(A^0\to q\bar{q})$ and $(h^0\to q\bar{q})(A^0\to\tau^+\tau^-)$. In the SM they occur with a branching ratio of about 10% in total. These channels play an important role in parts of the MSSM parameter space where the decays to $b\bar{b}$ are suppressed.

In the LEP1 phase only the *missing energy* and *leptonic* final states could be used in the search for the SM Higgs boson due to prohibitive background in the other channels. At LEP2, all search topologies are included.

The overall sensitivity is improved further by combining statistically the data of the four LEP experiments in different decay channels and at different LEP energies [6]. After preselection, the combined data configuration (distribution in several, global, discriminating variables) is compared to Monte Carlo configurations for two hypotheses: the pure SM background ("b") hypothesis, and the signal + background ("$s + b$") hypothesis where Higgs bosons are assumed to be produced along with the background according to the model under consideration. In the SM the model is fully defined by the test-mass m_H while in the MSSM it is defined by a set of parameters. The ratio $Q = \mathcal{L}_{s+b}/\mathcal{L}_b$ of the corresponding likelihoods is used as test-statistic to classify the observed data configuration between the "b" and "$s + b$" cases. The predicted, normalized, distributions of Q (probability density functions) are integrated to obtain the probabilities $1 - CL_b = 1 - \mathcal{P}_b(Q \leq Q_{observed})$ and $CL_{s+b} = \mathcal{P}_{s+b}(Q \leq Q_{observed})$, which measure the compatibility of the observed data configuration with the two hypotheses. For illustration, Figure 4 shows the LEP status of $-2\ln Q$ at ICHEP'2000 (Osaka) in July 2000 [7]. The

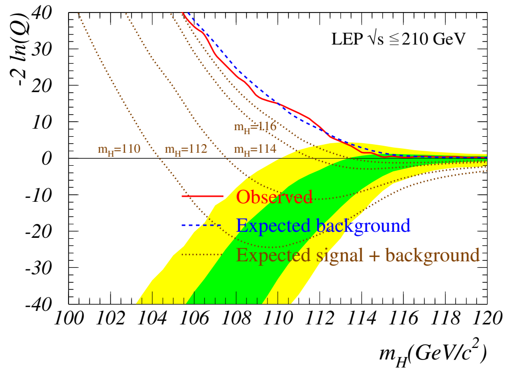

Figure 4. *The test-statistic $-2\ln Q$ as a function of the test-mass m_H [7]. The full curve (data) follows closely the "b" hypothesis (dashed) and deviates from the "$s+b$" predictions for various Higgs masses (dotted lines). The dark and light shaded areas are $\pm 1\sigma$ and $\pm 2\sigma$ bands about the predicted minima of $-2\ln Q$ in the "$s+b$" cases.*

configuration of the data followed closely the one expected from the background, and there was no indication for Higgs boson production.

5. Current status: SM Higgs boson

In the new data of the year 2000, mostly with $\sqrt{s}>$ 205 GeV, ALEPH reported an excess of about three standard deviations beyond the SM background [8] arising mainly from a few four-jet candidates with clean b-tags and kinematic properties suggesting a SM Higgs boson with mass in the vicinity of 115 GeV. DELPHI, L3 and OPAL do not see evidence for such an excess [9] and when the data of the four experiments are combined [10], the significance decreases to about two standard deviations. Figure 5 shows the test-statistic $-2\ln Q$ for the ALEPH data and for the LEP data combined. In the LEP data, the minimum is at 115.6 GeV defining the most likely value for the mass. From the probability density functions for m_{H^0}=115.6 GeV one calculates $1 - CL_b = 3.4\%$ for the "b" hypothesis. With $CL_{s+b} = 0.44$ the observed configuration is well within the "$s+b$" domain. From the same combination, a 95% c.l. lower bound of 114.1 GeV is obtained for the mass.

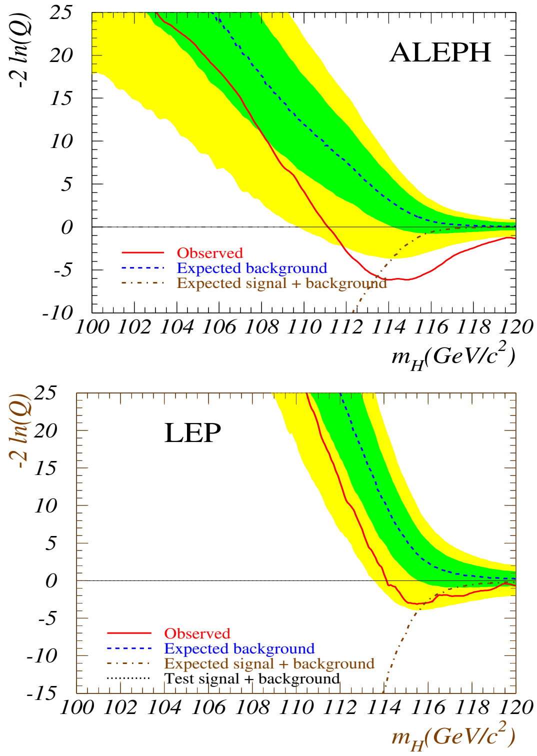

Figure 5. *Observed (solid line), and expected behaviours of the test-statistic $-2\ln Q$ for the "b" (dashed line) and the "$s+b$" (dash-dotted line) hypotheses as a function of the test mass m_H. Upper: ALEPH data alone; lower: LEP data combined [10]. The dark and light shaded bands represent $\pm 1\sigma$ and $\pm 2\sigma$ bands about of the "b" expectation.*

6. Neutral MSSM Higgs bosons

The presence of h^0 and A^0 bosons is tested at LEP in a constrained MSSM where universal soft SUSY-breaking masses $M_{\rm SUSY}$ and M_2 are assumed for sfermions and gauginos, respectively, at the electroweak scale. Further parameters are $\tan\beta$, m_{A^0}, the Higgs mixing parameter μ, and the trilinear coupling A. Most results assume the current experimental top quark mass of 174.3 GeV. The gluino mass $m_{\tilde{g}}$ affects the results via stop and sbottom loop corrections; it is fixed to 800 GeV. The Higgs decay width is taken to be small compared to the mass resolution, which is a valid assumption for $\tan\beta$ less than about 50.

The searches are interpreted in "benchmark" scenarios [11] where some of the parameters are fixed: $M_{\rm SUSY}$=1 TeV, $M_2 = 200$ GeV and $\mu = -200$ GeV. In the *no-mixing* benchmark scenario the stop mixing is put to zero by chosing $X_t \equiv A - \mu\cot\beta = 0$. The m_{h^0}-*max* benchmark scenario is designed to maximize m_{h^0} by chosing $X_t = 2M_{SUSY}$. This scenario yields the most conservative exclusion limits, in particular for $\tan\beta$.

The LEP-combined MSSM limits for the m_{h^0}-*max* scenario are shown in Figure 6 in the (m_{h^0}, $\tan\beta$) and (m_{A^0}, $\tan\beta$) projections (the individual experiments are referenced in [12]). The *no mixing* scenario is almost entirely excluded. The current 95% CL bounds are m_{h^0}>91.0 GeV, m_{A^0}>91.9 GeV. Values of $\tan\beta$ from 0.5 to 2.4 are excluded, but this exclusion can be smaller if e.g. the top mass is higher than the assumed value. The figure also displays exclusions at high $\tan\beta$ from the Tevatron CDF experiment searching for the Yukawa process $p\bar{p}\to b\bar{b}(h^0, A^0)X \to b\bar{b}b\bar{b}$ X [13].

7. Charged Higgs bosons in the 2HDM

The search for charged Higgs bosons is interpreted in the 2HDM where, in contrast to the MSSM, the mass is not constrained. The cross-section for $e^+e^-\to H^+H^-$ is fixed at the tree level by the mass $m_{H^\pm}$. Most LEP searches assume that the decay modes $H^+\to c\bar{s}$ and $\tau^+\nu$ fully exhaust the decay width. In the 2HDM the relative branching ratio is not predicted; the searches thus include the $(c\bar{s})(\bar{c}s)$, $(\tau^+\nu_\tau)(\tau^-\bar{\nu}_\tau)$ and $(c\bar{s})(\tau^-\bar{\nu}_\tau)$+$(\bar{c}s)(\tau^+\nu_\tau)$ final states. The current LEP-combined limit (contributions from the induvidual experiments are referenced in [14]) are reproduced in Figure 7 as a function of the branching ratio $B(H^+\to\tau^+\nu_\tau)$. The lowest bound, independent of the branching ratio, is currently 78.5 GeV.

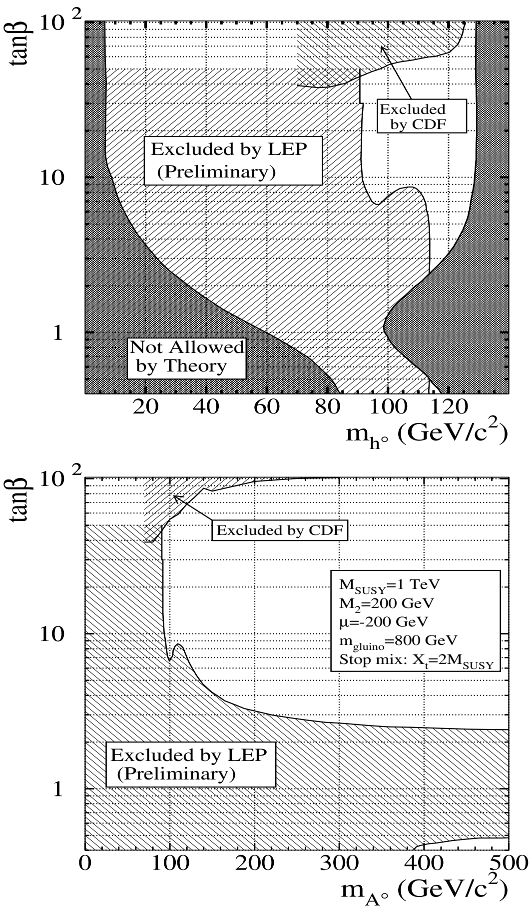

Figure 6. *The 95% c.l. bounds on m_{h^0}, m_{A^0} and $\tan\beta$ from LEP in the m_{h^0}-max benchmark scenario [12]. Exclusions at large $\tan\beta$ from the CDF [13] are also indicated.*

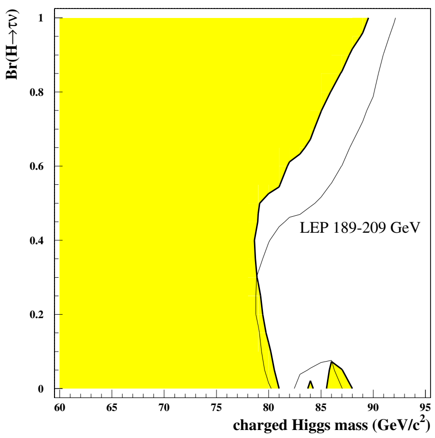

Figure 7. *The 95% CL bounds on* $m_{\mathrm{H}^\pm}$ *from LEP as a function of the branching ratio* $B(\mathrm{H}^+ \to \tau^+\nu_\tau)$ *[14]. The observed/expected exclusion limits are indicated by the heavy/light lines.*

8. Outlook

The LEP collider stopped producing data in Nov. 2000. At the Tevatron, the current sensitivity is rather limited for Higgs boson searches, but a powerful luminosity upgrade is in preparation. Performance studies [13] provide motivation for collecting large data samples, in excess of 10 fb^{-1} per experiment, which would extend the combined sensitivity of the CDF and D0 experiments beyond the LEP reach.

The Large Hadron Collider (LHC) will deliver proton-proton collisions at 14 TeV energy in the year 2006. The ATLAS and CMS detectors have been optimised for Higgs boson searches. The SM Higgs boson can be discovered between 100 GeV and 1 TeV mass. Full coverage of the MSSM parameter space will be provided, and several of the h^0, H^0, A^0 and H$^\pm$ bosons can be observed.

A high-energy e$^+$e$^-$ linear collider can be realised after the year 2010. Initially it could run at $\sqrt{s}$ up to 500 GeV with 1 TeV and more at a later stage. One of the prime goals would be to extend the precision measurements, typical of e$^+$e$^-$ colliders, to the Higgs sector. Finally, at a future $\mu^+\mu^-$ collider the Higgs bosons could be generated as s-channel resonances. Mass measurements with a few MeV precision would become possible and the widths could be obtained directly from a Breit-Wigner scan.

Finally, if Higgs bosons are not discovered at the TeV scale, both the LHC and the future lepton colliders would be in a position to test alternative theories of electroweak symmetry breaking such as those with strongly interacting vector bosons [15] expected in theories with dynamical symmetry breaking.

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