Higgs Bosons — H^0 and $H^{\pm}$, Searches for

SEARCHES FOR HIGGS BOSONS

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I. Introduction

One of the main challenges in high-energy physics is to understand electroweak symmetry breaking and the origin of mass. In the Standard Model (SM) [1], the electroweak interaction is described by a gauge field theory based on the $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ symmetry group. Masses can be introduced by the Higgs mechanism [2]. In its simplest form, which is implemented in the SM, fundamental scalar Higgs fields interact with each other such that they acquire non-zero vacuum expectation values, and the $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ symmetry is spontaneously broken down to the electromagnetic $\mathrm{U}(1)_{EM}$ symmetry. Gauge bosons and fermions obtain their masses by interacting with the vacuum Higgs fields. Associated with this description is the existence of massive scalar particles, Higgs bosons.

The minimal SM requires one Higgs field doublet, and predicts a single neutral Higgs boson, H^0. Beyond the SM, supersymmetric (SUSY) extensions [3] are of interest since they provide a consistent framework for the unification of the gauge interactions at a high energy scale, $\Lambda_{\mathrm{GUT}} \approx 10^{16}$ 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) (reviewed *e.g.*, in Ref. 4) is the SUSY extension of the SM with minimal new particle content. It introduces two Higgs field doublets, which is the minimal Higgs structure required to keep the theory free of anomalies, and to give masses to all charged fermions. The MSSM is a Two Higgs Doublet Model (2HDM) of "type II," where the neutral component of one field doublet couples to down quarks and charged leptons, while that of the other couples to up quarks only. Assuming CP invariance, the spectrum of MSSM 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, $H^{\pm}$.

Prior to 1989, when the e^+e^- collider LEP at CERN came into operation, the searches for Higgs bosons were sensitive to masses below a few GeV only (see Ref. 5 for a review). From 1989 to 1994 (the LEP1 phase), the LEP collider was operating at a center-of-mass energy $\sqrt{s} \approx M_Z$. After 1994 (the LEP2 phase), the center-of-mass energy increased each year, reaching 208 GeV in the year 2000 before the final shutdown. The combined data of the four LEP experiments, ALEPH, DELPHI, L3, and OPAL, are sensitive to Higgs bosons with masses up to the kinematic limit of the principal production processes, $e^+e^- \to H^0Z^0$ and h^0Z^0, that is, $(\sqrt{s})_{\rm max}{-}M_Z \approx 117$ GeV.

Searches have also been carried out at the Tevatron $p\overline{p}$ collider operating at $\sqrt{s} = 1.8$ TeV. With the currently available data samples, the sensitivity of the two experiments, CDF and DØ, is rather limited, but with increasing sample sizes, the range of sensitivity will eventually exceed the LEP range [6]. Later, the searches will continue at the LHC pp collider, covering masses up to about 1 TeV [7]. If Higgs bosons are indeed discovered, the Higgs mechanism could be studied in great detail at future e^+e^- [8,9] and $\mu^+\mu^-$ colliders [10].

In order to provide an up-to-date review, in some cases recent unpublished documents are also quoted. These are marked by (*) in the reference list, and can be accessed conveniently from the web page of Ref. 11 *("Information for PDG-2002")* . Results of the LEP Higgs Working Group (LHWG), obtained from combining the data of the four LEP experiments, can be accessed from Ref. 11 *("Papers")*. In each case, the LHWG documents list the papers from the individual experiments which have contributed to the combined result.

II. Higgs phenomenology

In this section, we summarize some features of the phenomenology [12,13] which govern the searches for Higgs bosons at LEP and at the Tevatron. Predictions for Higgs boson masses, as well as production and decay properties, are discussed.

Higgs boson masses

In the SM, the Higgs boson 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, and thus m_{H^0}, is not predicted, but arguments of self-consistency of the theory can be used to place approximate upper and lower bounds on m_{H^0} [14,15].

Since for large Higgs masses the running coupling λ rises with energy, the theory would eventually become nonperturbative. The requirement that in the SM this does not occur below a given energy scale Λ defines an upper bound for the Higgs mass. A lower bound is obtained from the study of quantum corrections to the SM effective potential. The requirement that the electroweak minimum remains an absolute minimum up to a scale Λ (or that the lifetime of the electroweak

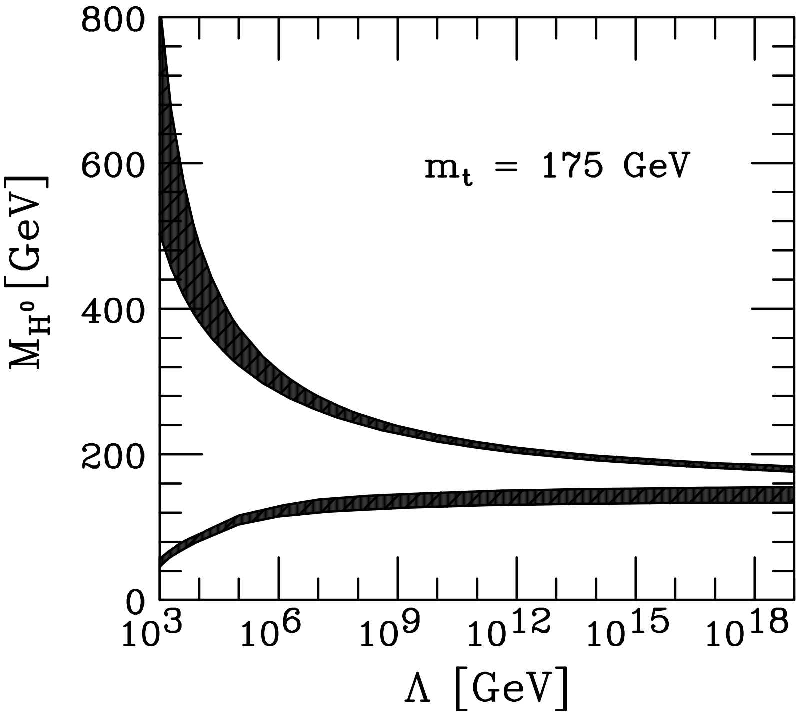

Figure 1: Bounds on the Higgs boson mass based on arguments of self-consistency of the SM (from Ref. 15). Λ denotes the energy scale at which the SM would become non-perturbative or the electroweak potential unstable.

minimum is large compared to the age of the universe) yields a "vacuum stability" condition which limits m_{H^0} from below.

These theoretical bounds are summarized in Fig. 1. If the SM is to be self-consistent up to $\Lambda_{\rm GUT} \approx 10^{16}$ GeV, there remains only a narrow band from about 130 to 190 GeV for the Higgs mass. Even stronger restrictions are obtained using arguments of naturalness and fine-tuning [16]. The discovery of a Higgs boson with mass below 130 GeV would suggest the onset of new physics at a scale below Λ_{GUT}, which is predicted, for example, by SUSY models. The dark bands in Fig. 1 represent theoretical uncertainties, with the top quark mass fixed at $m_t = 175$ GeV. For lower values of m_t, compatible with the measurements, the lower bound can be significantly softer.

Indirect experimental bounds for the SM Higgs boson mass are obtained from fits to precision measurements of electroweak observables, primarily from Z^0 decay data, and to the measured top and $W^{\pm}$ masses. These measurements are sensitive to $\log(m_{H^0})$ through radiative corrections. The best fit value is $m_{H^0} = 88^{+53}_{-35}$ GeV, or m_{H^0} <196 GeV at the 95% confidence level (CL) [17], which is still consistent with the SM being valid up to the GUT scale.

In the MSSM and at tree level, only two parameters are required (beyond known parameters of the SM fermion and gauge sectors) to fix all Higgs boson masses and couplings. A convenient choice is the mass m_{A^0} of the CP-odd scalar A^0, and the ratio $\tan\beta = v_2/v_1$ of the vacuum expectation values associated to the neutral components of the two Higgs fields (v_2 and v_1 couple to up and down fermions, respectively). Often the mixing angle α is used, which diagonalises the CP-even Higgs mass matrix; α can also be expressed in terms of m_{A^0} and $\tan\beta$. The following ordering of masses is valid at tree level: $m_{h^0} < (M_Z,\ m_{A^0}) < m_{H^0}$ and $M_W < m_{H^\pm}$. These relations are modified by radiative corrections [18,19]. The largest contribution arises from the incomplete cancelation between top and scalar-top (stop) loops. The corrections affect mainly the masses and decay branching ratios in the neutral Higgs sector; they depend strongly on the top quark mass ($\sim m_t^4$) and logarithmically on the stop masses, and involve a

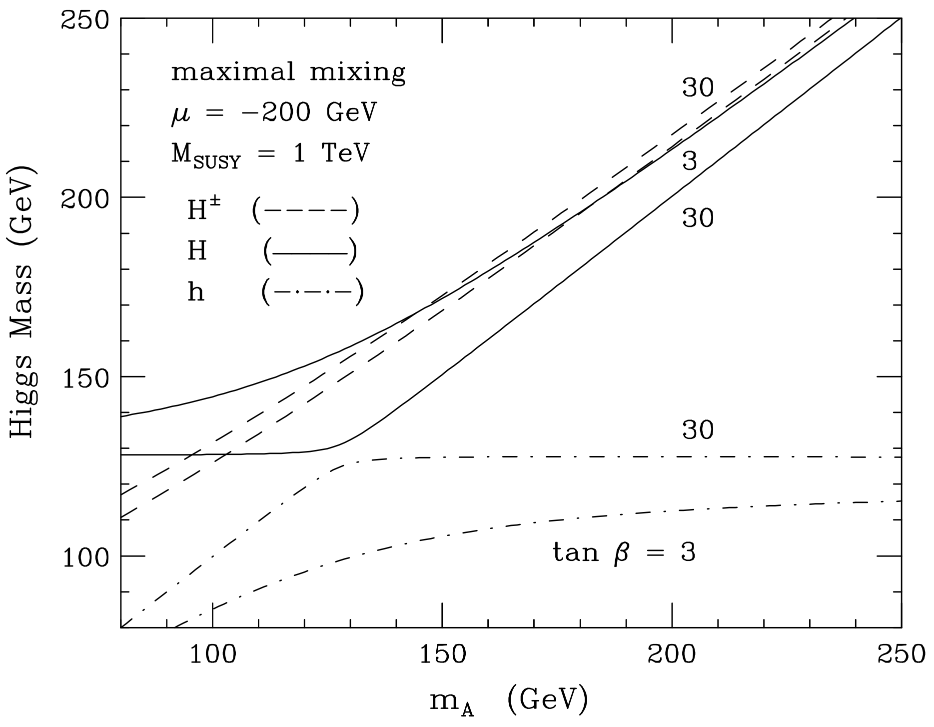

Figure 2: Higgs boson masses in the MSSM after radiative corrections, as a function of m_{A^0}, for $\tan\beta = 3$ and 30 (from Ref. 6).

detailed parameterization of soft SUSY breaking and the mixing between the SUSY partners of left- and right-handed top quarks (stop mixing).

The Higgs boson masses, after radiative corrections, are displayed in Fig. 2 for two representative values of $\tan\beta$ within the range from 1 to $\approx m_t/m_b$, which is preferred in some grand unification schemes [20], and in the simplest models of SUSY breaking.

Higgs boson production

The principal mechanism for producing the SM Higgs particle at LEP is Higgs-strahlung in the s-channel [21], $e^+e^- \to H^0Z^0$, where a Higgs boson is radiated off an intermediate Z^0 boson. The Z^0 boson in the final state is either virtual (LEP1) or on mass shell (LEP2). The cross section [22], $\sigma_{HZ}^{\rm SM}$, is shown in Fig. 3, together with those of the dominant SM background processes, $e^+e^- \to$ fermion pairs, W^+W^-, and Z^0Z^0.

The SM Higgs boson can also be produced by W^+W^- fusion in the t-channel [23], $e^+e^- \to \overline{\nu}_e\nu_eH^0$, but at LEP energies this process has a small contribution to the cross section, except for masses which cannot be reached by the Higgs-strahlung process. The contribution from Z^0Z^0 fusion, $e^+e^- \to e^+e^-H^0$, is insignificant.

In the 2HDM of "type II," of which the MSSM is a particular realization with SUSY, the main production mechanisms of the neutral Higgs bosons h^0 and A^0 are the Higgs-strahlung process $e^+e^- \to h^0Z^0$, and the pair production process $e^+e^- \to h^0A^0$. Fusion processes play a marginal role at LEP. The cross sections for Higgs-strahlung and pair production can be expressed in terms of the SM cross section $\sigma_{HZ}^{\rm SM}$, and the angles α and β introduced before:

$$\sigma_{h^0Z^0} = \sin^2(\beta-\alpha)\ \sigma_{HZ}^{\rm SM} \tag{1}$$

$$\sigma_{h^0A^0} = \cos^2(\beta-\alpha)\overline{\lambda}\ \sigma_{HZ}^{\rm SM}\ , \tag{2}$$

with the kinematic factor $\overline{\lambda} = \lambda_{A^0h^0}^{3/2}/\left[\lambda_{Z^0h^0}^{1/2}(12M_Z^2/s + \lambda_{Z^0h^0})\right]$ and $\lambda_{ij} = \left[1-(m_i+m_j)^2/s\right]\left[1-(m_i-m_j)^2/s\right]$. The two cross sections have complementary suppression factors $\sin^2(\beta-\alpha)$ and $\cos^2(\beta-\alpha)$. In the MSSM, the process $e^+e^- \to$

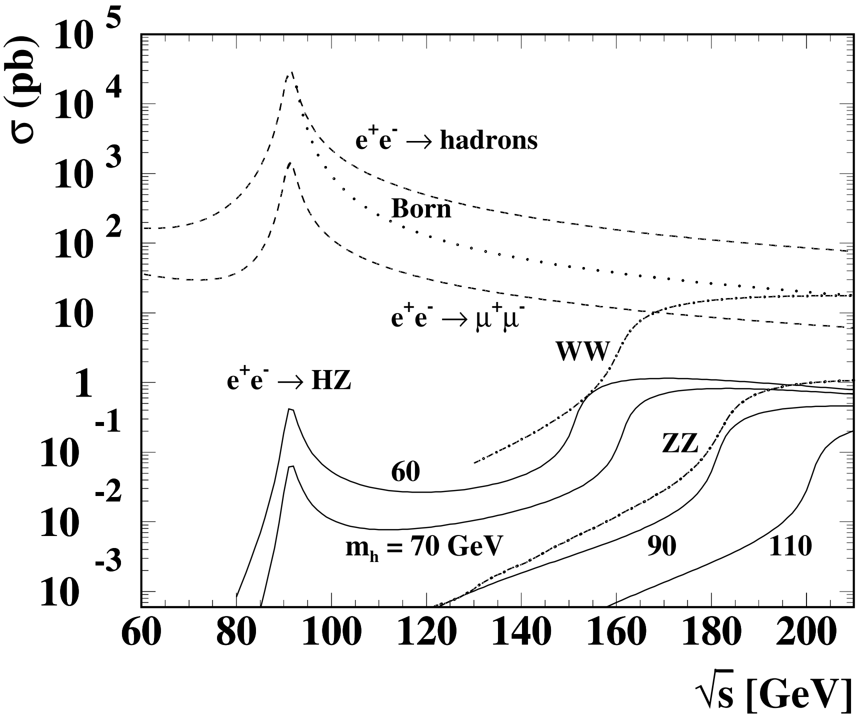

Figure 3: Cross sections, as a function of $\sqrt{s}$, for the Higgs-strahlung process in the SM for fixed values of m_{H^0} (full lines), and for other SM processes which contribute to the background.

$h^0 Z^0$ has the larger cross section at small $\tan\beta$, while at large $\tan\beta$ it is $e^+e^- \to h^0 A^0$, unless suppressed kinematically.

Charged Higgs bosons are expected to be produced at LEP in pairs [12,24], $e^+e^- \to H^+H^-$, and the cross section is fixed at tree level by the mass $m_{H^\pm}$.

At the Tevatron, the dominant production mechanism for the SM Higgs boson is gluon fusion, $gg \to H^0$ [25], but the mechanism with the most promising detection possibilities is the production in association with a vector boson, $p\overline{p} \rightarrow H^0V$ ($V \equiv W^{\pm},\ Z^0$), where the leptonic decays of the vector boson can be exploited for triggering [6]. The cross sections for this and other Higgs production processes are shown in Fig. 4.

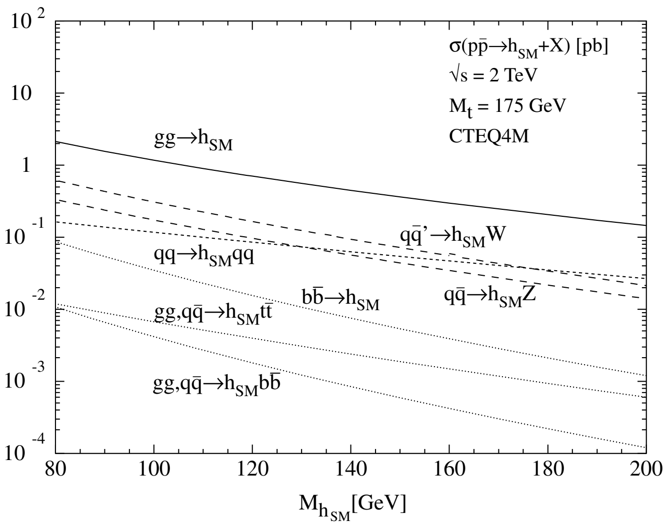

Figure 4: Cross sections (in units of pb), as a function of the mass, for the most relevant SM Higgs production processes in $p\overline{p}$ collisions at $\sqrt{s} = 2$ TeV (from Ref. 6).

Over most of the MSSM parameter space, one of the CP-even Higgs bosons (h^0 or H^0) couples to the vector bosons with SM-like strength. Like in the SM case, the associated production, $p\overline{p} \to (h^0$ or $H^0)V$ (with $V \equiv W^{\pm}$, Z^0), is the most promising search mechanism. The gluon fusion processes, $gg \to h^0$, H^0, A^0, are dominant, but in this case, only the Higgs to $\tau^+\tau^-$ decay mode is promising, since the main $b\overline{b}$ decay mode is overwhelmed by QCD background.

Charged Higgs bosons with mass less than $m_t - m_b$ can be produced at the Tevatron in the decay of the top quark, $t \to H^+ b$. This process can compete with the SM decay, $t \to W^+ b$, depending on the value of $\tan\beta$. Assuming that no other decay process contributes, the cross section for charged Higgs production in top quark decay is related to the $t\overline{t}$ cross section and the $t^+ \to W^+ b$ branching ratio:

$$\sigma(p\overline{p} \to H^{\pm}+\mathrm{X}) = \left[1 - \mathrm{BR}(t \to W^+ b)^2\right] \;\; \sigma(p\overline{p} \to t\overline{t}+\mathrm{X}). \quad (3)$$

Higgs boson decays

The most relevant decays of the SM Higgs particle [22,24] are summarized in Fig. 5. For masses below about 140 GeV, decays to fermion anti-fermion pairs dominate, and $H^0 \to b\overline{b}$ has the largest branching ratio. Decays to $\tau^+\tau^-$, $c\overline{c}$, and gluon pairs (via loops) contribute less than 10%. For such low masses, the decay width is less than 10 MeV. For larger masses, the W^+W^- and Z^0Z^0 final states dominate and the decay width rises rapidly with mass, reaching about 1 GeV for $m_{H^0} = 200$ GeV, and 100 GeV for $m_{H^0} = 500$ GeV.

In the 2HDM of "type II," and thus in the MSSM, the couplings of the neutral Higgs bosons to quarks, leptons, and gauge bosons are modified with respect to the SM Higgs

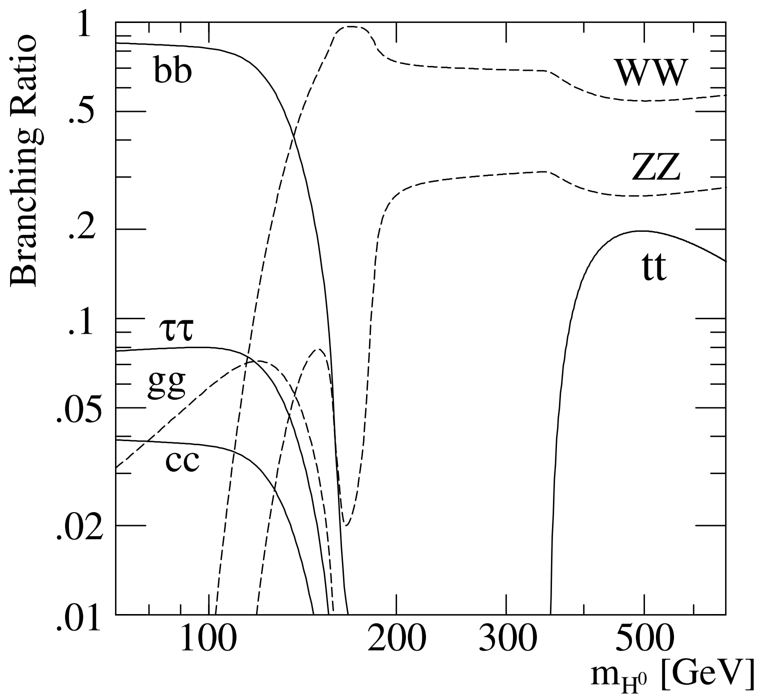

Figure 5: Branching ratios for the main decay modes of the SM Higgs boson (from Ref. 8).

couplings by factors which depend upon the angles α and β. These factors, valid at tree level, are summarized in Table 1.

The following features are relevant to decays of neutral Higgs bosons in the MSSM. The h^0 boson will decay mainly to fermion pairs, since the mass is smaller than about 130 GeV. The A^0 boson also decays predominantly to fermion pairs, independently of its mass, since its coupling to vector bosons is zero at leading order (see Table 1). For $\tan\beta > 1$, decays to $b\overline{b}$ and $\tau^+\tau^-$ pairs are preferred, with branching ratios of about 90% and 8%, respectively, while the decays to $c\overline{c}$ and gluon

Table 1: Factors relating the 2HDM Higgs couplings to the couplings in the SM.

	"Up" fermions	"Down" fermions	Vector bosons
SM Higgs:	1	1	1
2HDM h^0 :	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
H^0 :	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
A^0 :	$1/\tan\beta$	$\tan\beta$	0

pairs are suppressed. Decays to $c\overline{c}$ may become important for $\tan\beta$ <1. The decay $h^0 \to A^0A^0$ may become dominant if it is kinematically allowed. Other possible decays go to SUSY particles such as sfermions, charginos or neutralinos, which may lead to invisible or barely visible final states. The branching fractions for such decays can be dominant in parts of the MSSM parameter space, thus requiring special search strategies.

The charged Higgs bosons of the 2HDM decay mainly via $H^+ \to \tau^+\nu_\tau$ if $\tan\beta$ is large. For small $\tan\beta$, the decay to $c\overline{s}$ is dominant at low mass, and the decay to $H^+ \to t^*\overline{b} \to W^+b\overline{b}$ is dominant for $m_{H^\pm}$ larger than about 130 GeV [26].

III. Searches for the SM Higgs boson

During the LEP1 phase, the experiments ALEPH, DELPHI, L3, and OPAL analyzed over 17 million Z^0 decays. They have set lower bounds of approximately 65 GeV on the mass of the SM Higgs boson, and of about 45 GeV on the masses of the h^0, A^0 (valid for $\tan\beta$ >1), and $H^\pm$ bosons [27]. Substantial data samples have also been collected at LEP2 energies, including more than 40,000 $e^+e^- \to W^+W^-$ events. At LEP2, the composition of the background is more complex than at LEP1 (see Fig. 3), due to the additional SM processes

$e^+e^- \to W^+W^-$ and Z^0Z^0. These have kinematic properties similar to the signal, especially for $m_{H^0} \sim M_W$ and M_Z, but since at LEP2 the Z^0 boson is on mass shell, constrained kinematic fits yield sufficient separation power. Furthermore, the four collaborations have considerably upgraded their b-tagging capabilities for LEP2. Jets with b flavor (such as from Higgs boson decays) are recognized by the presence of secondary decay vertices, or tracks with large impact parameters identified by means of high-precision silicon microvertex detectors. Other useful indicators for b flavor are high-p_T leptons from $b \to c\ell^-\overline{\nu}_\ell$ decays ($\ell = e, \mu$) and several jet properties, all of which are combined using likelihood or neural network techniques.

The following final states provide good sensitivity for the SM Higgs boson.

(a) The most abundant, four-jet topology is produced in the $e^+e^- \to (H^0 \to b\overline{b})(Z^0 \to q\overline{q})$ process, and occurs with a branching ratio of about 60%. The invariant mass of two jets is close to M_Z, while the other two jets contain b flavor. The Higgs boson mass is reconstructed with a typical resolution of 2.5 GeV.

(b) The missing energy topology is produced mainly in the $e^+e^- \to (H^0 \to b\overline{b})(Z^0 \to \nu\overline{\nu})$ process, and occurs with a branching ratio of 17%. The signal has two b jets, substantial missing transverse momentum, and missing mass compatible with M_Z. The reconstruction of the Higgs boson mass is achieved with a typical "central" resolution of 3 GeV, but the distribution has pronounced tails. A similar event topology also occurs in the W^+W^- fusion process leading to $b\overline{b}\nu_e\overline{\nu}_e$.

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

(d) Final states with tau leptons are produced in the processes $e^+e^- \to (H^0 \to \tau^+\tau^-)(Z^0 \to q\overline{q})$ and $(H^0 \to q\overline{q})(Z^0 \to \tau^+\tau^-)$. They occur with a branching ratio of about 10% in total.

At LEP1, only the missing energy and leptonic final states could be used in the search for the SM Higgs boson, because of prohibitive backgrounds in the other channels. At LEP2, however, all search topologies are included.

The overall sensitivity of the searches is improved by combining statistically the data of the four LEP experiments in different decay channels, and at different LEP energies [28]. After preselection, the combined data configuration (distribution in several global, discriminating variables) is compared in a frequentist approach to Monte Carlo configurations for two hypotheses: the background (b) hypothesis, and the signal + background ($s+b$) hypothesis, where Higgs bosons are assumed to be produced according to the model under consideration: in the case of the SM, the Higgs couplings are fully defined by the hypothesized Higgs boson mass ("test mass") m_H, while in the MSSM and other cases, the model may be 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 position 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 $1 - \mathrm{CL}_b = 1 - \mathcal{P}_b(Q \leq Q_{\mathrm{observed}})$ and $\mathrm{CL}_{s+b} = \mathcal{P}_{s+b}(Q \leq Q_{\mathrm{observed}})$, which measure the compatibility of the observed data configuration with the two hypotheses.

The searches carried out at LEP prior to the year 2000, and their successive combinations [29], did not reveal any evidence for the production of an SM Higgs boson. In the data of the year 2000, mostly with $\sqrt{s} > 205$ GeV, ALEPH reported an excess of about three-standard deviations beyond the SM background [30], 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. The data of DELPHI, L3, and OPAL show no evidence for such an excess, but do not, however, exclude a 115 GeV Higgs boson (see Ref. 31 for the individual publications). When the data of the four experiments are combined [32], the significance decreases to about two standard deviations.

Figure 6 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 $m_H = 115.6$ GeV, one calculates $1 - \mathrm{CL}_b = 3.4\%$ for the background hypothesis. With $\mathrm{CL}_{s+b} = 0.44$, the observed data configuration is well compatible with the signal + background hypothesis. From the same combination, a 95% CL lower bound of 114.1 GeV is obtained for the mass. Note that these LEP-combined results are based on a preliminary analysis of ALEPH, DELPHI, and OPAL data, and the final analysis of the L3 data.

At the Tevatron, the results of the CDF [33] and DØ [34] collaborations are currently based on the Run I data samples of about 100 pb^{-1} each. The searches concentrate on the associated production of a Higgs boson with a vector boson, $p\overline{p} \to VH^0$ ($V \equiv Z^0, W^{\pm}$), where the vector boson decays into the leptonic channels $W^{\pm} \to \ell^{\pm}\nu$ and $Z^0 \to \ell^+\ell^-$ ($\ell \equiv e,\ \mu$). CDF also considers hadronic decays, and DØ includes the

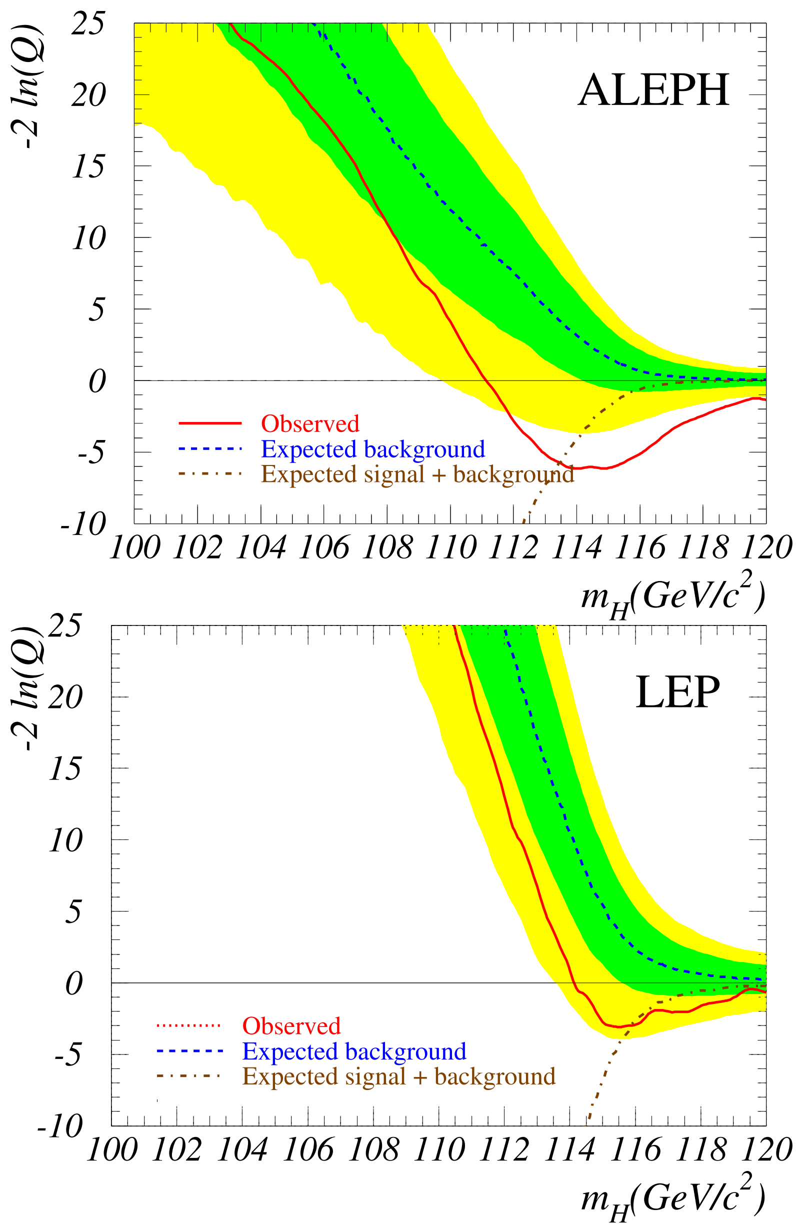

Figure 6: Observed (solid line), and expected behaviors of the test statistic $-2\ln Q$ for the background (dashed line), and the signal + background hypothesis (dash-dotted line), as a function of the test mass m_H. Upper: ALEPH data alone; lower: LEP data combined [32]. The dark- and light-shaded bands represent one and two standard deviation bands about the background expectation.

$Z^0 \to \nu\overline{\nu}$ channel. The Higgs boson is assumed to decay into $b\overline{b}$, which is the dominant channel below about 140 GeV mass. Both CDF and DØ have the capability to tag b jets using high-p_T leptons from the $b \to c\ell^-\overline{\nu}$ decay; in the case of CDF, the b tag is made more effective by detecting secondary decay vertices in their silicon microvertex detector. The main source of background is from QCD processes with genuine $b\overline{b}$ pairs.

The current data samples are too small for a discovery, but allow model-independent upper bounds to be set on the cross section for Higgs-like event topologies. These bounds are currently higher by an order of magnitude than the SM predictions; however, Run II started in the year 2001, and with the projected data samples in excess of 10 fb^{-1} per experiment, the search sensitivity will increase considerably.

IV. Searches for neutral MSSM Higgs bosons

The searches at LEP address the Higgs-strahlung process $e^+e^- \to h^0Z^0$, and the pair production process $e^+e^- \to h^0A^0$, exploiting the complementarity of the cross sections expressed in Equations (1) and (2). The results for h^0Z^0 are obtained by re-interpreting the SM Higgs searches, taking into account the reduction of the cross section due to the MSSM factor $\sin^2(\beta-\alpha)$. The results for h^0A^0 are obtained from specific searches for $(b\overline{b})(b\overline{b})$, and $\tau^+\tau^-q\overline{q}$ final states (the $\tau^+\tau^-$ pair may originate from the decay of h^0 or A^0).

The presence of h^0 and/or A^0 is tested in a constrained MSSM model where universal soft SUSY breaking masses, $M_{\rm SUSY}$ and M_2, are assumed for sfermions and SU(2)$\times$U(1) gauginos, respectively, at the electroweak scale. Further parameters are m_{A^0}, $\tan\beta$, the Higgs mixing parameter μ, and the trilinear Higgs-fermion coupling A. Most results assume the current experimental top quark mass of 174.3 GeV [35].

Furthermore, the gluino mass, which affects the results at the two-loop level, is fixed at 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.

Although general parameter scans have been carried out [36], most interpretations are limited to specific "benchmark" scenarios [19] 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, stop mixing is put to zero by choosing $X_t \equiv A - \mu\cot\beta = 0$. The m_{h^0}-max benchmark scenario is designed to maximize m_{h^0} by choosing $X_t = 2M_{\rm SUSY}$. This scenario yields the most conservative exclusion limits, in particular, regarding the value of $\tan\beta$.

The combined LEP limits in the MSSM parameter space [37] are shown in Fig. 7 for the m_{h^0}*-max* scenario (in the *no-mixing* scenario, the unexcluded region is much smaller). The current 95% CL mass bounds are: m_{h^0} >91.0 GeV, m_{A^0} >91.9 GeV. Furthermore, values of $\tan\beta$ from 0.5 to 2.4 are excluded, but this exclusion can be smaller if, for example, the top mass turns out to be higher than assumed, or $\mathcal{O}(\alpha_t^2 m_t^2)$ two-loop corrections to $m^2_{h^0}$ are included in the model calculation.

The CDF experiment has searched for the Yukawa process $p\overline{p} \rightarrow b\overline{b}\ \phi \rightarrow b\overline{b}b\overline{b}$ [38], where a Higgs particle ($\phi \equiv h^0$, H^0, A^0) is radiated off a b quark and decays to $b\overline{b}$. This process is enhanced in the MSSM at large $\tan\beta$, where the Yukawa coupling to b quarks is large. The domains excluded by CDF are indicated in Fig. 7, along with the limits from LEP.

V. Searches for charged Higgs bosons

While in the MSSM the mass of the charged Higgs boson is restricted essentially to $m_{H^\pm} > M_W$, such a restriction does not exist in the 2HDM. The searches conducted at LEP and at

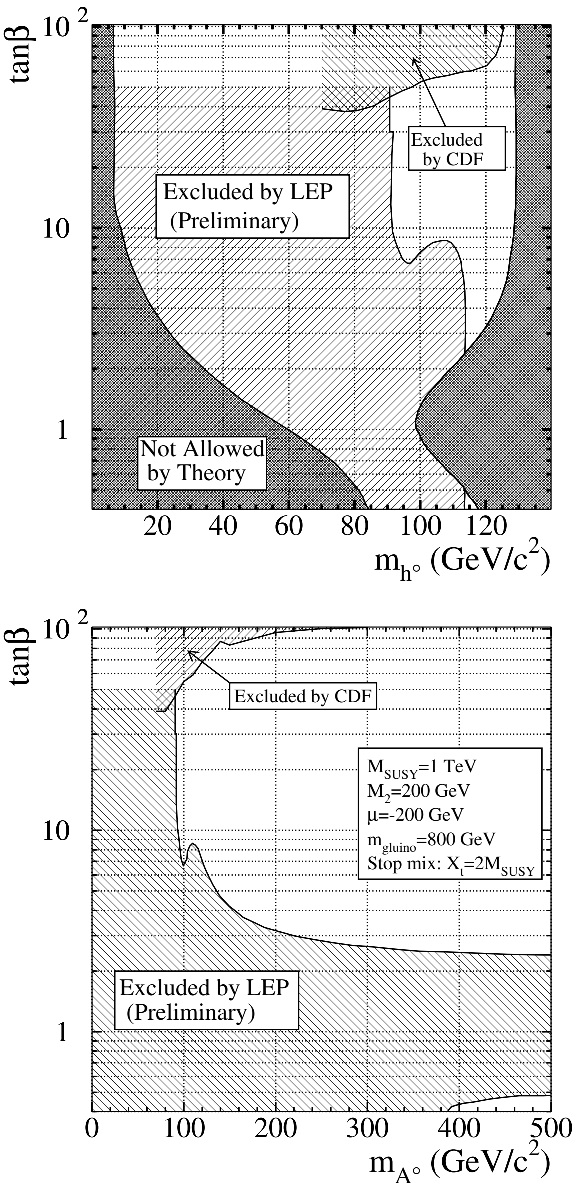

Figure 7: The 95% CL bounds on m_{h^0}, m_{A^0}, and $\tan\beta$ for the m_{h^0}-max benchmark scenario, from LEP [37]. The exclusions at large $\tan\beta$ from CDF [38] are also indicated.

the Tevatron are, therefore, interpreted primarily in the 2HDM of "type II."

At LEP, charged Higgs bosons are expected to be produced in the process $e^+e^- \to H^+H^-$, and to decay via $H^+ \to c\overline{s}$

and $\tau^+\nu$. While it is assumed that these two channels fully exhaust the decay width, the relative branching ratio is left free. The following three final states are therefore considered: $(c\overline{s})(\overline{c}s)$, $(\tau^+\nu_\tau)(\tau^-\overline{\nu}_\tau)$, and $(c\overline{s})(\tau^-\overline{\nu}_\tau)+(\overline{c}s)(\tau^+\nu_\tau)$. At LEP2 energies, the sensitivity is limited to masses less than M_W by the background from $e^+e^- \to W^+W^-$. The data of the four LEP experiments have been combined, resulting in a general mass bound of $m_{H^\pm} >$78.6 GeV (95% CL) [39], which is independent of the branching ratio BR($H^+ \to \tau^+\nu$).

The searches at the Tevatron look for charged Higgs bosons in the decay of the top quark, $t \to bH^+$. While the SM requires the top quark to decay almost exclusively via $t \to bW^+$, in the 2HDM the process $t \to bH^+$ may compete if $m_{H^+} < m_t - m_b$, and if $\tan\beta$ is either larger than 30 or less than one. The DØ collaboration has adopted an indirect "disappearance technique" optimized for the detection of $t \to bW^+$, and a direct search for $t \to bH^+ \to b\tau^+\nu_\tau$ [40]. CDF has reported on the direct search for $t \to bH^+$ [41], and on an indirect approach [42] in which the rate of dileptons and lepton+jets in top quark decays is compared to the SM prediction. Both collaborations assume that the H^+ decays into three channels: (i) $c\overline{s}$, which is dominant at low $\tan\beta$ and small $m_{H^\pm}$, (ii) $t^*\overline{b} \to W^+b\overline{b}$, dominant at low $\tan\beta$ and for $m_{H^\pm} \approx m_t + m_b$, and (iii) $\tau^+\nu_\tau$, dominant at high $\tan\beta$. The results from the Tevatron are summarized in Fig. 8, together with the exclusion obtained at LEP. The Tevatron limits are subject to potentially large theoretical uncertainties [43].

Indirect limits in the ($m_{H^\pm}$, $\tan\beta$) plane can be derived by comparing the measured rate of the flavor-changing neutral-current process $b \to s\gamma$ to the SM prediction. In the SM, this process is mediated by virtual $W^\pm$ exchange, and gives rise to

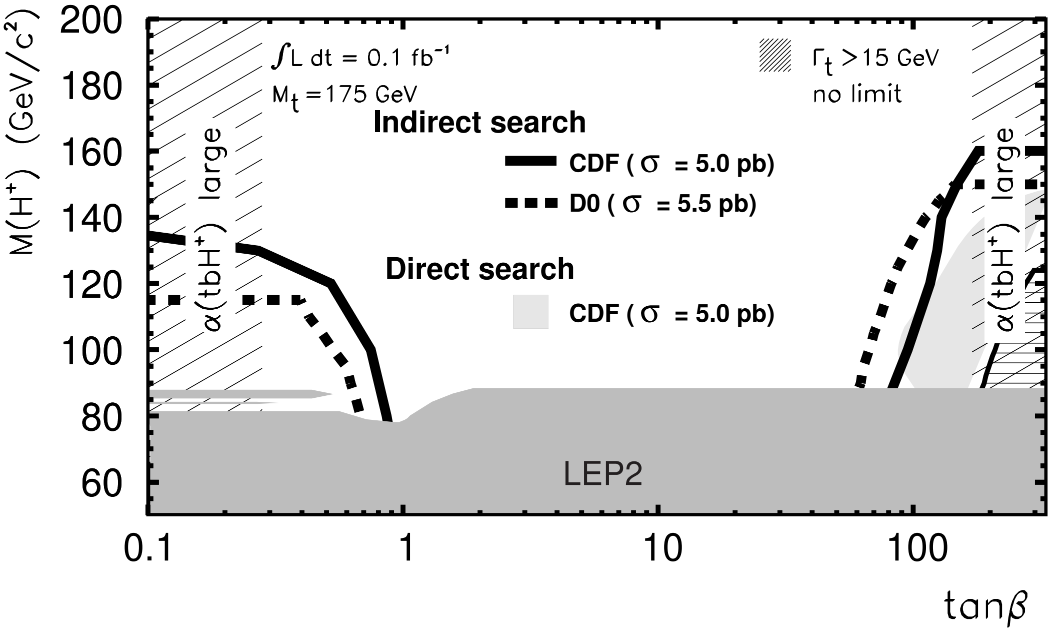

Figure 8: Summary of the 95% CL exclusions in the $(m_{H^+}, \tan\beta)$ plane from DØ [40] and CDF [41], using various indirect and direct observation techniques (the regions below the curves are excluded). The two experiments use slightly different theoretical $t\bar{t}$ cross sections, as indicated. The dashed domains at extreme values of $\tan\beta$ are not considered in these searches, since there the tbH^+ coupling becomes large, and perturbative calculations do not apply. The dark region labeled LEP2 is excluded by LEP [39].

a branching ratio of $(3.60 \pm 0.30) \times 10^{-4}$, according to a recent evaluation [44]. In the 2HDM of "type II," the branching ratio is altered by contributions from charged Higgs bosons [45]. The current experimental value, $(3.23 \pm\ 0.42) \times 10^{-4}$ [44], obtained from combining the measurements of CLEO, BELLE, and ALEPH [46], is in agreement with the SM prediction. From the comparison, the bound $m_{H^\pm}$ >316 GeV (95% CL) is obtained, which is much stronger than the current bounds from direct searches. However, these indirect bounds are model-dependent and may be invalidated, for example, by sparticle loops or anomalous couplings. Other, less stringent, indirect bounds are obtained from interpretations of measured $b \to \tau^- \nu_\tau$X rates and tau lepton decay properties at LEP [47].

VI. Model extensions

(a) Most of the searches for the processes $e^+e^- \to h^0 Z^0$ and $h^0 A^0$, which have been addressed in Section IV, rely on the experimental signature of Higgs bosons decaying into $b\overline{b}$. While this assumption is valid over large parts of the MSSM parameter space, in the 2HDM, the h^0 and A^0 decaying to non-$b\overline{b}$ final states may be strongly enhanced. Recently flavor-independent searches have been carried out by the LEP experiments which do not apply b-tagging requirements [48]. In conjunction with the earlier b-flavor sensitive searches, large domains of the general 2HDM parameter space of "type II" could be excluded [49].

(b) The neutral Higgs bosons h^0 and A^0 can also be produced by Yukawa processes $e^+e^- \to f\overline{f}h^0$ and $f\overline{f}A^0$, where these are radiated off a massive fermion ($f \equiv$ b or $\tau^\pm$). These processes can be dominant in regions of the 2HDM space, where the "standard" processes, $e^+e^- \to h^0 Z^0$ and $h^0 A^0$, are suppressed. The corresponding enhancement factors (ratios of the 2HDM $f\overline{f}h^0$ and $f\overline{f}A^0$ couplings to the SM $f\overline{f}H^0$ coupling) are $\sin\alpha/\cos\beta$ and $\tan\beta$, respectively. The LEP data have been analyzed, searching specifically for $b\overline{b}b\overline{b}$, $b\overline{b}\tau^+\tau^-$, and $\tau^+\tau^-\tau^+\tau^-$ final states [50]. Regions of low mass and high enhancement factors are excluded by these searches. The CDF search for the analogous $pp \to b\overline{b}$ X process [38] has already been discussed (see Fig. 7).

(c) Higgs bosons with double electric charge, $H^{\pm\pm}$, are predicted by several extensions of the SM, for example, with additional triplet scalar fields or left-right symmetric models [12,51]. OPAL has searched for the process $Z^0 \to H^{++}H^{--}$ with four prompt electrons or muons in the final state, and obtained model-dependent lower bounds in the vicinity of 93 GeV for the mass [52].

(d) The addition of a singlet scalar field to the MSSM [53] gives rise to two additional neutral scalars, one CP-even and one CP-odd. The radiative corrections to the masses are similar to those in the MSSM, and arguments of perturbative continuation to the GUT scale lead to an upper bound of about 135-140 GeV for the mass of the lightest neutral CP-even scalar. DELPHI have reinterpreted their searches for neutral Higgs bosons to constrain such models [54].

(e) Decays into invisible (weakly interacting neutral) particles may occur, for example, in the MSSM, if the Higgs bosons decay to pairs of neutralinos. In a different context, Higgs bosons might also decay into pairs of massless Goldstone bosons or Majorons [55]. In the process $e^+e^- \to h^0Z^0$, the mass of the invisible Higgs boson can be inferred from the reconstructed Z^0 boson, using the beam energy constraint. The LEP results have recently been combined, and yield a 95% CL lower bound of 114.4 GeV for the mass of a Higgs boson, with SM production rate and decaying exclusively into invisible final states [56].

(f) Photonic final states from the processes $e^+e^- \to Z^0/\gamma^* \to H^0\gamma$ and from $H^0 \to \gamma\gamma$ do not occur in the SM at tree level, but may be present with a low rate due to $W^\pm$ and top quark loops [57]. Additional loops, for example, from SUSY particles, would increase the rates only slightly [58], but models with anomalous couplings predict enhancements by orders of magnitude. Searches for the processes $e^+e^- \rightarrow (H^0 \rightarrow b\overline{b})\gamma$, $(H^0 \rightarrow \gamma\gamma)q\overline{q}$, and $(H^0 \rightarrow \gamma\gamma)\gamma$ have been used to set model-independent limits on such anomalous couplings. They were also used to constrain very specific models leading to an enhanced $H^0 \rightarrow \gamma\gamma$ rate, such as the "fermiophobic" 2HDM of "type I" [59], where all fermions couple to the same Higgs field component, and the fermionic decays can thus be suppressed simultaneously by appropriate parameter choices. The searches at LEP have recently been combined [60], and exclude a fermiophobic Higgs boson with mass less than 108.2 GeV (95% CL). Limits of about 80 GeV are obtained at the Tevatron [61].

VII. Prospects

The LEP collider stopped producing data in November 2000. At the Tevatron, Run II started in 2001. Performance studies provide motivation for collecting data samples in excess of 10 fb^{-1} per experiment, which will extend the combined sensitivity of CDF and DØ for the SM Higgs boson search beyond the LEP reach, and allow large domains in the MSSM parameter space to be investigated [6].

The Large Hadron Collider (LHC) should deliver proton-proton collisions at 14 TeV in the year 2007. The ATLAS and CMS detectors have been optimized for Higgs boson searches [7]. The discovery of the SM Higgs boson will be possible over the mass range between 100 GeV and 1 TeV. This broad range is covered by a variety of production and decay processes. The LHC experiments will provide full coverage of the MSSM parameter space by direct searches for the h^0, H^0, A^0, and $H^{\pm}$ bosons, and by detecting the h^0 boson in cascade decays of SUSY particles. The discovery of several Higgs bosons is possible over extended domains of the parameter space. Decay branching fractions can be determined and masses measured with statistical accuracies between 10^{-3} (at 400 GeV mass) and 10^{-2} (at 700 GeV mass).

A high-energy e^+e^- linear collider could be realized after the year 2010, running initially at energies up to 500 GeV, and at 1 TeV or more at a later stage [9]. One of the prime goals would be to extend the precision measurements typical of e^+e^- colliders to the Higgs sector. At such a collider, the Higgs couplings to fermions and vector bosons can be measured with precisions of a few percent. The MSSM parameters can be studied in great detail. At the highest collider energies and luminosities, the self-coupling of the Higgs fields can be studied directly through final states with two Higgs bosons [62].

At a future $\mu^+\mu^-$ collider, the Higgs bosons can be generated as s-channel resonances [10]. Mass measurements with precisions of a few MeV would be possible, and the widths could be obtained directly from Breit-Wigner scans. The heavy CP-even and CP-odd bosons H^0 and A^0, degenerate over most of the MSSM parameter space, could be disentangled experimentally.

Finally, if Higgs bosons are not discovered at the TeV scale, both the LHC and the future lepton colliders will be in a position to test alternative theories of electroweak symmetry breaking, such as those with strongly interacting vector bosons [63] expected in theories with dynamical symmetry breaking [64].

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STANDARD MODEL H^0 (Higgs Boson) MASS LIMITS

These limits apply to the Higgs boson of the three-generation Standard Model with the minimal Higgs sector. For a review and a bibliography, see the above Note on 'Searches for Higgs Bosons' by P. Igo-Kemenes.

Limits from Coupling to $Z/W^{\pm}$

Limits on the Standard Model Higgs obtained from the study of Z^0 decays rule out conclusively its existence in the whole mass region $m_{H^0} \lesssim 60$ GeV. These limits, as well as stronger limits obtained from e^+e^- collisions at LEP at energies up to 172 GeV, and weaker limits obtained from other sources, have been superseded by the most recent data of LEP. They have been removed from this compliation, and are documented in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this Review of Particle Physics.

In this Section, unless otherwise stated, limits from the four LEP experiments (ALEPH, DELPHI, L3, and OPAL) are obtained from the study of the $e^+e^- \rightarrow H^0 Z$ process, at center-of-mass energies reported in the comment lines.

A combination of then unpublished results from the four LEP experiments, carried out in LEP 01 by the LEP Higgs Working Group in the Summer 2001, has led to a 95% CL limit of $m_H > 114.1$ GeV. See the Higgs minireview for details.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>111.5	95	[1,2,3] HEISTER	02	ALEP	$E_{cm} \leq 209$ GeV
>109.7	95	[1] ABBIENDI	01C	OPAL	$E_{cm} \leq 209$ GeV
>114.3	95	[1] ABREU	01E	DLPH	$E_{cm} \leq 209$ GeV
>112.0	95	[1] ACHARD	01C	L3	$E_{cm} \leq 209$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>107.3	95	[1] ABDALLAH	02B	DLPH	$E_{cm} \leq 202$ GeV
		[4] ABAZOV	01E	D0	$p\overline{p} \rightarrow H^0 WX, H^0 ZX$
>107.0	95	[5] ACCIARRI	01B	L3	$E_{cm} \leq 202$ GeV
>107.7	95	[1] BARATE	01C	ALEP	$E_{cm} \leq 202$ GeV
		[1] ACCIARRI	00U	L3	$E_{cm} \leq 209$ GeV
>110.6	95	[1,2] BARATE	00U	ALEP	$E_{cm} \leq 209$ GeV
		[6] ABE	98T	CDF	$p\overline{p} \rightarrow H^0 WX, H^0 ZX$

[1] Search for $e^+e^- \to H^0 Z$ in the final states $H^0 \to b\overline{b}$ with $Z \to \ell\overline{\ell}$, $\nu\overline{\nu}$, $q\overline{q}$, $\tau^+\tau^-$ and $H^0 \to \tau^+\tau^-$ with $Z \to q\overline{q}$.

[2] A 3σ excess of candidate events compatible with m_{H^0} near 114 GeV is observed in the combined channels $q\overline{q}q\overline{q}$, $q\overline{q}\ell\overline{\ell}$, $q\overline{q}\tau^+\tau^-$.

[3] HEISTER 02 updates BARATE 00U.

[4] ABAZOV 01E search for associated $H^0 W$ and $H^0 Z$ production in $p\overline{p}$ collisions at $E_{\rm cm}$= 1.8 TeV. The limits of $\sigma(H^0 W)\times$B$(W \to e\nu)\times$B$(H^0 \to q\overline{q}) < 2.0$ pb (95%CL) and $\sigma(H^0 Z)\times$B$(Z \to e^+e^-)\times$B$(H^0 \to q\overline{q}) < 0.8$ pb (95%CL) are given for m_H=115 GeV.

[5] Search for $e^+e^- \to H^0 Z$ in the final states $H^0 \to q\overline{q}$ with $Z \to \ell^+\ell^-$, $\nu\overline{\nu}$, $q\overline{q}$, and $\tau^+\tau^-$, and $H^0 \to \tau^+\tau^-$ with $Z \to q\overline{q}$.

[6] ABE 98T search for associated $H^0 W$ and $H^0 Z$ production in $p\overline{p}$ collisions at $\sqrt{s}$= 1.8 TeV with $W(Z) \to q\overline{q}^{(\prime)}$, $H^0 \to b\overline{b}$. The results are combined with the search in ABE 97W, resulting in the cross-section limit $\sigma(H^0 + W/Z)\cdot$B$(H^0 \to b\overline{b})<$(23–17) pb (95%CL) for m_H= 70–140 GeV. This limit is one to two orders of magnitude larger than the expected cross section in the Standard Model.

H^0 Indirect Mass Limits from Electroweak Analysis

For limits obtained before the direct measurement of the top quark mass, see the 1996 (Physical Review **D54** 1 (1996)) Edition of this Review. Other studies based on data available prior to 1996 can be found in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this Review. For indirect limits obtained from other considerations of theoretical nature, see the Note on "Searches for Higgs Bosons."

Because of the high current interest, we mention here the following unpublished result (LEP 00, and update, presented by A. Straessner at the 2000 Electroweak Rencontres de Moriond) although we do not include it in the Listings or Tables: m_H= 66.5^{+60}_{-33} GeV. This is obtained from a fit to LEP, SLD, W mass, top mass, and neutrino scattering data available in the Spring of 2000, with $1/\alpha^{(5)}(m_Z)$= 128.878 ± 0.090. The 95%CL upper limit is 188 GeV.

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
390^{+750}_{-280}		[7] ABBIENDI 01A	OPAL	
		[8] CHANOWITZ 99	RVUE	
<290	95	[9] D'AGOSTINI 99	RVUE	
<211	95	[10] FIELD 99	RVUE	
		[11] CHANOWITZ 98	RVUE	
$170^{+150}_{-\ 90}$		[12] HAGIWARA 98B	RVUE	
$141^{+140}_{-\ 77}$		[13] DEBOER 97B	RVUE	
$127^{+143}_{-\ 71}$		[14] DEGRASSI 97	RVUE	$\sin^2\theta_W$(eff,lept)
$158^{+148}_{-\ 84}$		[15] DITTMAIER 97	RVUE	
$149^{+148}_{-\ 82}$		[16] RENTON 97	RVUE	
$145^{+164}_{-\ 77}$		[17] ELLIS 96C	RVUE	
185^{+251}_{-134}		[18] GURTU 96	RVUE	

[7] ABBIENDI 01A make Standard Model fits to OPAL's measurements of Z-lineshape parameters and lepton forward-backward asymmetries, using m_t=174.3 ± 5.1 GeV and $1/\alpha(m_Z)$ = 128.90 ± 0.09. The fit also yields $\alpha_s(m_Z)$=0.127 ± 0.005. If the external value of $\alpha_s(m_Z)$=0.1184 ± 0.0031 is added to the fit, the result changes to $m_{H^0}=190^{+335}_{-165}$ GeV.

[8] CHANOWITZ 99 studies LEP/SLD data on 9 observables related $\sin^2\theta^{\ell}_{\rm eff}$, available in the Spring of 1998. A scale factor method is introduced to perform a global fit, in view of the conflicting data. m_H as large as 750 GeV is allowed at 95% CL.

[9] D'AGOSTINI 99 use m_t, m_W, and effective $\sin^2\theta_W$ from LEP/SLD available in the Fall 1998 and combine with direct Higgs search constraints from LEP2 at $E_{\rm cm}$=183 GeV. $\alpha(m_Z)$ given by DAVIER 98.

[10] FIELD 99 studies the data on b asymmetries from $Z^0 \rightarrow b\overline{b}$ decays at LEP and SLD (from LEP 99). The limit uses $1/\alpha(M_Z)$= 128.90 ± 0.09, the variation in the fitted top quark mass, $m_t=171.2^{+3.7}_{-3.8}$ GeV, and excludes b-asymmetry data. It is argued that exclusion of these data, which deviate from the Standard Model expectation, from the electroweak fits reduces significantly the upper limit on m_H. Including the b-asymmetry data gives instead the 95%CL limit $m_H < 284$ GeV. See also FIELD 00.

[11] CHANOWITZ 98 fits LEP and SLD Z-decay-asymmetry data (as reported in ABBANEO 97), and explores the sensitivity of the fit to the weight ascribed to measurements that are individually in significant contradiction with the direct-search limits. Various prescriptions are discussed, and significant variations of the 95%CL Higgs-mass upper limits are found. The Higgs-mass central value varies from 100 to 250 GeV and the 95%CL upper limit from 340 GeV to the TeV scale.

[12] HAGIWARA 98B fit to LEP, SLD, W mass, and neutrino scattering data as reported in ALCARAZ 96, with m_t = 175 ± 6 GeV, $1/\alpha(m_Z)$= 128.90 ± 0.09 and $\alpha_s(m_Z)$= 0.118 ± 0.003. Strong dependence on m_t is found.

[13] DEBOER 97B fit to LEP and SLD data (as reported in ALCARAZ 96), as well as m_W and m_t from CDF/DØ and CLEO $b \rightarrow s\gamma$ data (ALAM 95). $1/\alpha(m_Z)$ = 128.90 ± 0.09 and $\alpha_s(m_Z)$ = 0.120 ± 0.003 are used. Exclusion of SLC data yields $m_H=241^{+218}_{-123}$ GeV. $\sin^2\theta_{\rm eff}$ from SLC (0.23061 ± 0.00047) would give $m_H=16^{+16}_{-9}$ GeV.

[14] DEGRASSI 97 is a two-loop calculation of M_W and $\sin^2\theta^{\rm lept}_{\rm eff}$ as a function of m_H, using $\sin^2\theta^{\rm lept}_{\rm eff}$ 0.23165(24) as reported in ALCARAZ 96, m_t = 175 ± 6 GeV, and $1/\alpha(m_Z)$=128.90 ± 0.09.

[15] DITTMAIER 97 fit to m_W and LEP/SLC data as reported in ALCARAZ 96, with m_t = 175 ± 6 GeV, $1/\alpha(m_Z^2)$ = 128.89 ± 0.09. Exclusion of the SLD data gives $m_H = 261^{+224}_{-128}$ GeV. Taking only the data on m_t, m_W, $\sin^2\theta^{\rm lept}_{\rm eff}$, and $\Gamma^{\rm lept}_Z$, the authors get $m_H = 190^{+174}_{-102}$ GeV and $m_H = 296^{+243}_{-143}$ GeV, with and without SLD data, respectively. The 95% CL upper limit is given by 550 GeV (800 GeV removing the SLD data).

[16] RENTON 97 fit to LEP and SLD data (as reported in ALCARAZ 96), as well as m_W and m_t from $p\overline{p}$, and low-energy νN data available in early 1997. $1/\alpha(m_Z) = 128.90 \pm 0.09$ is used.

[17] ELLIS 96C fit to LEP, SLD, m_W, neutral-current data available in the summer of 1996, plus m_t = 175 ± 6 GeV from CDF/DØ . The fit yields m_t = 172 ± 6 GeV.

[18] GURTU 96 studies the effect of the mutually incompatible SLD and LEP asymmetry data on the determination of m_H. Use is made of data available in the Summer of 1996. The quoted value is obtained by increasing the errors *à la* PDG. A fit ignoring the SLD data yields 267^{+242}_{-135} GeV.

MASS LIMITS FOR NEUTRAL HIGGS BOSONS IN SUPERSYMMETRIC MODELS

The minimal supersymmetric model has two complex doublets of Higgs bosons. The resulting physical states are two scalars [H_1^0 and H_2^0, where we define $m_{H_1^0} < m_{H_2^0}$], a pseudoscalar (A^0), and a charged Higgs pair ($H^\pm$). H_1^0 and H_2^0 are also called h and H in the literature. There are two free parameters in the theory which can be chosen to be m_{A^0} and $\tan\beta = v_2/v_1$, the ratio of vacuum expectation values of the two Higgs doublets. Tree-level Higgs masses are constrained by the model to be $m_{H_1^0} \leq m_Z$, $m_{H_2^0} \geq m_Z$, $m_{A^0} \geq m_{H_1^0}$, and $m_{H^\pm} \geq m_W$. However, as described in the Review on Supersymmetry in this Volume these relations are violated by radiative corrections.

Unless otherwise noted, the experiments in e^+e^- collisions search for the processes $e^+e^- \rightarrow H_1^0 Z^0$ in the channels used for the Standard Model Higgs searches and $e^+e^- \rightarrow H_1^0 A^0$ in the final states $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$. Limits on the A^0 mass arise from these direct searches, as well as from the relations valid in the minimal supersymmetric model between m_{A^0} and $m_{H_1^0}$. As discussed in the minireview on Supersymmetry, in this volume, these relations depend on the masses of the t quark and $\widetilde{t}$ squark. The limits are weaker for larger t and $\widetilde{t}$ masses, while they increase with the inclusion of two-loop radiative corrections. To include the radiative corrections to the Higgs masses, unless otherwise stated, the listed papers use the two-loop results with $m_t = 175$ GeV, the universal scalar mass of 1 TeV, SU(2) gaugino mass of 200 GeV, and the Higgsino mass parameter $\mu = -200$ GeV, and examine the two scenarios of no scalar top mixing and 'maximal' stop mixing (which maximizes the effect of the radiative correction).

The mass region $m_{H_1^0} \lesssim 45$ GeV has been by now entirely ruled out by measurements at the Z pole. The relative limits, as well as other by now obsolete limits from different techniques, have been removed from this compilation, and can be found in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this Review. Unless otherwise stated, the following results assume no invisible H_1^0 or A^0 decays.

H_1^0 (Higgs Boson) MASS LIMITS in Supersymmetric Models

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$>$ 85.9	95	[19,20] ABDALLAH	02B	DLPH	$E_{cm} \leq 202$ GeV, $\tan\beta > 0.49$
> 89.8	95	[20,21] HEISTER	02	ALEP	$E_{cm} \leq 209$ GeV, $\tan\beta > 0.5$
$>$ 83.4	95	[20,22] ACCIARRI	01C	L3	$E_{cm} \leq 202$ GeV, $\tan\beta > 0.8$
$>$100	95	[23] AFFOLDER	01D	CDF	$p\overline{p} \rightarrow b\overline{b}H_1^0$, $\tan\beta \gtrsim 55$
$>$ 74.8	95	[24] ABBIENDI	00F	OPAL	$E_{cm} \leq 189$ GeV, $\tan\beta > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>$ 91.2	95	[20,25] BARATE	01C	ALEP	$E_{cm} \leq 202$ GeV, $\tan\beta > 0.5$
$>$ 75	95	[26] ABREU,P	00B	DLPH	$E_{cm} \leq 189$ GeV

[19] ABDALLAH 02B also search for the final state $H^0_1 A^0 \rightarrow 3A^0 \rightarrow b\overline{b}b\overline{b}b\overline{b}$. See their Fig. 18 for the limits in the scenario in which B($H^0_1 \rightarrow b\overline{b}$)=0, and Fig. 19 for results with a scan of the general MSSM parameter space.

[20] Search for $e^+e^- \rightarrow H^0_1 A^0$ in the final states $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$, and $e^+e^- \rightarrow H^0_1 Z$. Universal scalar mass of 1 TeV, SU(2) gaugino mass of 200 GeV, and $\mu= -200$ GeV are assumed, and two-loop radiative corrections incorporated. The limits hold for m_t=175 GeV and for stop mixing leading to the most conservative Higgs mass limit.

[21] HEISTER 02 excludes the range 0.7 <tanβ < 2.3. A wider range is excluded with different stop mixing assumptions. Updates BARATE 01C.

[22] Updates the results of ACCIARRI 99U.

[23] AFFOLDER 01D search for final states with 3 or more b-tagged jets. See Figs. 2 and 3 for Higgs mass limits as a function of tanβ, and for different stop mixing scenarios. Stronger limits are obtained at larger tanβ values.

[24] ABBIENDI 00F search for $e^+e^- \rightarrow H^0_1 A^0$ in the final states $b\overline{b}b\overline{b}$, $b\overline{b}\tau^+\tau^-$, and $A^0A^0A^0 \rightarrow b\overline{b}b\overline{b}b\overline{b}$, and $e^+e^- \rightarrow H^0_1 Z$. Universal scalar mass of 1 TeV, SU(2) gaugino mass of 1.63 TeV and Higgsino mass parameter μ=−0.1 TeV are assumed. m_t=175 GeV is used. The cases of maximal and no-stop mixing are examined. Limits obtained from scans of the Supersymmetric parameter space can be found in the paper. Updates the results of ABBIENDI 99E.

[25] Updates the results of BARATE 00F.

[26] ABREU,P 00B search for $e^+e^- \rightarrow H^0_1 A^0$ in the final state $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$, and $e^+e^- \rightarrow H^0_1 Z$. Full two-loop radiative corrections are incorporated. A scan of the MSSM parameters space is performed, assuming $m_{A^0} > 20$ GeV, universal scalar mass m_0 and SU(2) gaugino mass in the range 0.2–1 TeV and Higgsino mass parameter $|\mu| < 0.5$ TeV. m_t=175 GeV is used. The cases of maximal and no-stop mixing are examined. These results update ABREU 00G.

A^0 (Pseudoscalar Higgs Boson) MASS LIMITS in Supersymmetric Models

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 86.5	95	[27,28] ABDALLAH	02B	DLPH	$E_{cm} \leq 202$ GeV, tan$\beta > 0.49$
> 90.1	95	[28,29] HEISTER	02	ALEP	$E_{cm} \leq 209$ GeV, tan$\beta > 0.5$
> 83.8	95	[28,30] ACCIARRI	01C	L3	$E_{cm} \leq 202$ GeV, tan$\beta > 0.8$
>100	95	[31] AFFOLDER	01D	CDF	$p\overline{p} \rightarrow b\overline{b}A^0$, tan$\beta \gtrsim 55$
> 76.5	95	[32] ABBIENDI	00F	OPAL	$E_{cm} \leq 189$ GeV, tan$\beta > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 91.6	95	[28,33] BARATE	01C	ALEP	$E_{cm} \leq 202$ GeV, tan$\beta > 0.5$
> 78	95	[34] ABREU,P	00B	DLPH	$E_{cm} \leq 189$ GeV

[27] ABDALLAH 02B also search for the final state $H^0_1 A^0 \rightarrow 3A^0 \rightarrow b\overline{b}b\overline{b}b\overline{b}$. See their Fig. 18 for the limits in the scenario in which B($H^0_1 \rightarrow b\overline{b}$)=0, and Fig. 19 for results with a scan of the general MSSM parameter space.

[28] Search for $e^+e^- \rightarrow H^0_1 A^0$ in the final states $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$, and $e^+e^- \rightarrow H^0_1 Z$. Universal scalar mass of 1 TeV, SU(2) gaugino mass of 200 GeV, and $\mu= -200$ GeV are assumed, and two-loop radiative corrections incorporated. The limits hold for m_t=175 GeV and for stop mixing leading to the most conservative Higgs mass limit.

[29] HEISTER 02 excludes the range 0.7 <tanβ < 2.3. A wider range is excluded with different stop mixing assumptions. Updates BARATE 01C.

[30] Updates the results of ACCIARRI 99U.

[31] AFFOLDER 01D search for final states with 3 or more b-tagged jets. See Figs. 2 and 3 for Higgs mass limits as a function of tanβ, and for different stop mixing scenarios. Stronger limits are obtained at larger tanβ values.

[32] ABBIENDI 00F search for $e^+e^- \rightarrow H^0_1 A^0$ in the final states $b\overline{b}b\overline{b}$, $b\overline{b}\tau^+\tau^-$, and $A^0A^0A^0 \rightarrow b\overline{b}b\overline{b}b\overline{b}$, and $e^+e^- \rightarrow H^0_1 Z$. Universal scalar mass of 1 TeV, SU(2) gaugino mass of 1.63 TeV and Higgsino mass parameter $\mu=-0.1$ TeV are assumed. m_t=175 GeV is used. The cases of maximal and no-stop mixing are examined. Limits obtained from scans of the Supersymmetric parameter space can be found in the paper. Updates the results of ABBIENDI 99E.

[33] Updates the results of BARATE 00F.

[34] ABREU,P 00B search for $e^+e^- \rightarrow H^0_1 A^0$ in the final state $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$, and $e^+e^- \rightarrow H^0_1 Z$. Full two-loop radiative corrections are incorporated. A scan of the MSSM parameters space is performed, assuming $m_{A^0} > 20$ GeV, universal scalar mass m_0 and SU(2) gaugino mass in the range 0.2–1 TeV and Higgsino mass parameter $|\mu| < 0.5$ TeV. m_t=175 GeV is used. The cases of maximal and no-stop mixing are examined. These results update ABREU 00G.

H^0 (Higgs Boson) MASS LIMITS in Extended Higgs Models

This Section covers models which do not fit into either the Standard Model or its simplest minimal Supersymmetric extension (MSSM), leading to anomalous production rates, or nonstandard final states and branching ratios. In particular, this Section covers limits which may apply to generic two-Higgs-doublet models (2HDM), or to special regions of the MSSM parameter space where decays to invisible particles or to photon pairs are dominant (see the Note on 'Searches for Higgs Bosons' at the beginning of this Chapter). See the footnotes or the comment lines for details on the nature of the models to which the limits apply.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>105.4	95	[35] ACHARD	02C	L3	$H^0_1 \rightarrow \gamma\gamma$
>114.1	95	[36] HEISTER	02	ALEP	Invisible H^0, $E_{cm} \leq 209$ GeV
none 1–44	95	[37] ABBIENDI	01E	OPAL	H^0_1, Type-II model
none 12–56	95	[37] ABBIENDI	01E	OPAL	A^0, Type-II model
>107	95	[38] ABREU	01F	DLPH	$H^0_1 \rightarrow \gamma\gamma$
> 98	95	[39] AFFOLDER	01H	CDF	$p\overline{p} \rightarrow H^0 W/Z$, $H^0 \rightarrow \gamma\gamma$
>106.4	95	[36] BARATE	01C	ALEP	Invisible H^0, $E_{cm} \leq 202$ GeV
> 89.2	95	[40] ACCIARRI	00M	L3	Invisible H^0
		[41] ACCIARRI	00R	L3	$e^+e^- \rightarrow H^0\gamma$ and/or $H^0 \rightarrow \gamma\gamma$
		[42] ACCIARRI	00R	L3	$e^+e^- \rightarrow e^+e^- H^0$
> 94.9	95	[43] ACCIARRI	00S	L3	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow \gamma\gamma$
>100.7	95	[44] BARATE	00L	ALEP	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow \gamma\gamma$
> 68.0	95	[45] ABBIENDI	99E	OPAL	$\tan\beta > 1$
> 96.2	95	[46] ABBIENDI	99O	OPAL	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow \gamma\gamma$
> 78.5	95	[47] ABBOTT	99B	D0	$p\overline{p} \rightarrow H^0 W/Z$, $H^0 \rightarrow \gamma\gamma$
		[48] ABREU	99P	DLPH	$e^+e^- \rightarrow H^0\gamma$ and/or $H^0 \rightarrow \gamma\gamma$
> 76.1	95	[49] ABREU	99Q	DLPH	Invisible H^0
		[50] GONZALEZ-G..	98B	RVUE	Anomalous coupling
		[51] KRAWCZYK	97	RVUE	$(g-2)_\mu$
		[52] ALEXANDER	96H	OPAL	$Z \rightarrow H^0\gamma$
		[53] ABREU	95H	DLPH	$Z \rightarrow H^0 Z^*$, $H^0 A^0$
		[54] PICH	92	RVUE	Very light Higgs

[35] ACHARD 02C search for associated production of a $\gamma\gamma$ resonance with a Z boson, followed by $Z \rightarrow q\overline{q}$, $\ell^+\ell^-$, or $\nu\overline{\nu}$, at $E_{cm} \leq 209$ GeV. The limit is for a H^0 with SM production cross section and B($H^0 \rightarrow f\overline{f}$)=0 for all fermions f. For B($H^0 \rightarrow \gamma\gamma$)=1, $m_{H^0} > 114$ GeV is obtained.

[36] HEISTER 02 and BARATE 01C search for $e^+e^- \rightarrow H^0 Z$ with H^0 decaying invisibly. The limit assumes SM production cross section and B($H^0 \rightarrow$ invisible) = 1.

[37] ABBIENDI 01E search for neutral Higgs bosons in general Type-II two-doublet models, at $E_{cm} \leq 189$ GeV. In addition to usual final states, the decays H^0_1, $A^0 \rightarrow q\overline{q}$, gg are searched for. See their Figs. 15,16 for excluded regions.

[38] ABREU 01F search for neutral, fermiophobic Higgs bosons in Type-I two-doublet models, at $E_{cm} \leq 202$ GeV. The limit is from $e^+e^- \rightarrow H^0 Z$ with the SM cross section and B($H^0 \rightarrow \gamma\gamma$)=1. The process $e^+e^- \rightarrow H^0 A^0$ with $H^0 \rightarrow \gamma\gamma$ is also searched for in the modes $A^0 \rightarrow b\overline{b}$, $H^0 Z$ and long-lived A^0. See their Figs. 4–6 for the excluded regions.

[39] AFFOLDER 01H search for associated production of a $\gamma\gamma$ resonance and a W or Z (tagged by two jets, an isolated lepton, or missing E_T). The limit assumes Standard Model values for the production cross section and for the couplings of the H^0 to W and Z bosons. See their Fig. 11 for limits with B($H^0 \rightarrow \gamma\gamma$)< 1.

[40] ACCIARRI 00M search for $e^+e^- \rightarrow Z H^0$ with H^0 decaying invisibly at E_{cm}=183–189 GeV. The limit assumes SM production cross section and B($H^0 \rightarrow$ invisible)=1. See their Fig. 6 for limits for smaller branching ratios.

[41] ACCIARRI 00R search for $e^+e^- \rightarrow H^0\gamma$ with $H^0 \rightarrow b\overline{b}$, $Z\gamma$, or $\gamma\gamma$. See their Fig. 3 for limits on $\sigma \cdot$B. Explicit limits within an effective interaction framework are also given, for which the Standard Model Higgs search results are used in addition.

[42] ACCIARRI 00R search for the two-photon type processes $e^+e^- \rightarrow e^+e^- H^0$ with $H^0 \rightarrow b\overline{b}$ or $\gamma\gamma$. See their Fig. 4 for limits on $\Gamma(H^0 \rightarrow \gamma\gamma)\cdot$B($H^0 \rightarrow \gamma\gamma$ or $b\overline{b}$) for m_{H^0}=70–170 GeV.

[43] ACCIARRI 00S search for associated production of a $\gamma\gamma$ resonance with a $q\overline{q}$, $\nu\overline{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- collisions at E_{cm}= 189 GeV. The limit is for a H^0 with SM production cross section and B($H^0 \rightarrow f\overline{f}$)=0 for all fermions f. For B($H^0 \rightarrow \gamma\gamma$)=1, $m_{H^0} > 98$ GeV is obtained. See their Fig. 5 for limits on B($H \rightarrow \gamma\gamma$)$\cdot\sigma(e^+e^- \rightarrow H f\overline{f})/\sigma(e^+e^- \rightarrow H f\overline{f})$ (SM).

[44] BARATE 00L search for associated production of a $\gamma\gamma$ resonance with a $q\overline{q}$, $\nu\overline{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- collisions at E_{cm}= 88–202 GeV. The limit is for a H^0 with SM production cross section and B($H^0 \rightarrow f\overline{f}$)=0 for all fermions f. For B($H^0 \rightarrow \gamma\gamma$)=1, $m_{H^0} > 109$ GeV is obtained. See their Fig. 3 for limits on B($H \rightarrow \gamma\gamma$)$\cdot\sigma(e^+e^- \rightarrow H f\overline{f})/\sigma(e^+e^- \rightarrow H f\overline{f})$ (SM).

[45] ABBIENDI 99E search for $e^+e^- \rightarrow H^0 A^0$ and $H^0 Z$ at E_{cm} = 183 GeV. The limit is with m_H=m_A in general two Higgs-doublet models. See their Fig. 18 for the exclusion limit in the m_H–m_A plane. Updates the results of ACKERSTAFF 98S.

[46] ABBIENDI 99O search for associated production of a $\gamma\gamma$ resonance with a $q\overline{q}$, $\nu\overline{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- collisions at 189 GeV. The limit is for a H^0 with SM production cross section and B($H^0 \rightarrow f\overline{f}$)=0, for all fermions f. See their Fig. 4 for limits on $\sigma(e^+e^- \rightarrow H^0 Z^0)\times$B($H^0 \rightarrow \gamma\gamma$)$\times$B($X^0 \rightarrow f\overline{f}$) for various masses. Updates the results of ACKERSTAFF 98Y.

[47] ABBOTT 99B search for associated production of a $\gamma\gamma$ resonance and a dijet pair. The limit assumes Standard Model values for the production cross section and for the couplings of the H^0 to W and Z bosons. Limits in the range of $\sigma(H^0 + Z/W)\cdot$B($H^0 \rightarrow \gamma\gamma$)= 0.80–0.34 pb are obtained in the mass range m_{H^0}= 65–150 GeV.

[48] ABREU 99P search for $e^+e^- \rightarrow H^0\gamma$ with $H^0 \rightarrow b\overline{b}$ or $\gamma\gamma$, and $e^+e^- \rightarrow H^0 q\overline{q}$ with $H^0 \rightarrow \gamma\gamma$. See their Fig. 4 for limits on $\sigma\times$B. Explicit limits within an effective interaction framework are also given.

[49] ABREU 99Q search for $e^+e^- \rightarrow H^0 Z$ with H^0 decaying invisibly at E_{cm} between 161 and 183 GeV. The limit assumes SM production cross section, and holds for any B($H^0 \rightarrow$ invisible). In the case of invisible decays in the MSSM, the excluded region of the (M_2, tanβ) plane overlaps the exclusion region from direct searches for charginos and neutralinos (ABREU 99E in the Supersymmetry Listings). See their Fig. 6(d) for limits on a Majoron model.

[50] GONZALEZ-GARCIA 98B use DØ limit for $\gamma\gamma$ events with missing E_T in $p\overline{p}$ collisions (ABBOTT 98) to constrain possible ZH or WH production followed by unconventional $H \rightarrow \gamma\gamma$ decay which is induced by higher-dimensional operators. See their Figs. 1 and 2 for limits on the anomalous couplings.

[51] KRAWCZYK 97 analyse the muon anomalous magnetic moment in a two-doublet Higgs model (with type II Yukawa couplings) assuming no $H_1^0 ZZ$ coupling and obtain $m_{H_1^0} \gtrsim$ 5 GeV or $m_{A^0} \gtrsim$ 5 GeV for tan$\beta > 50$. Other Higgs bosons are assumed to be much heavier.

[52] ALEXANDER 96H give B($Z \rightarrow H^0\gamma$)$\times$B($H^0 \rightarrow q\overline{q}$) < 1–4×10^{-5} (95%CL) and B($Z \rightarrow H^0\gamma$)$\times$B($H^0 \rightarrow b\overline{b}$) < 0.7–2×10^{-5} (95%CL) in the range $20 < m_{H^0} < 80$ GeV.

[53] See Fig. 4 of ABREU 95H for the excluded region in the $m_{H^0} - m_{A^0}$ plane for general two-doublet models. For tan$\beta > 1$, the region $m_{H^0}+m_{A^0} \lesssim 87$ GeV, $m_{H^0} < 47$ GeV is excluded at 95% CL.

[54] PICH 92 analyse H^0 with $m_{H^0} < 2m_\mu$ in general two-doublet models. Excluded regions in the space of mass-mixing angles from LEP, beam dump, and $\pi^\pm$, η rare decays are shown in Figs. 3,4. The considered mass region is not totally excluded.

$H^\pm$ (Charged Higgs) MASS LIMITS

Unless otherwise stated, the limits below assume B($H^+ \rightarrow \tau^+\nu$)+B($H^+ \rightarrow c\overline{s}$)=1, and hold for all values of B($H^+ \rightarrow \tau^+\nu_\tau$), and assume H^+ weak isospin of T_3=+1/2. In the following, tanβ is the ratio of the two vacuum expectation values in two-doublet models (2HDM).

The limits are also applicable to point-like technipions. For a discussion of techniparticles, see the Review of Dynamical Electroweak Symmetry Breaking in this Review.

For limits obtained in hadronic collisions before the observation of the top quark, and based on the top mass values inconsistent with the current measurements, see the 1996 (Physical Review **D54** 1 (1996)) Edition of this Review.

Searches in e^+e^- collisions at and above the Z pole have conclusively ruled out the existence of a charged Higgs in the region $m_{H^+} \lesssim 45$ GeV, and are now superseded by the most recent searches in higher energy e^+e^- collisions at LEP. Results by now obsolete are therefore not included in this compilation, and can be found in the previous Edition (The European Physical Journal **C15** 1 (2000)) of this Review.

In the following, and unless otherwise stated, results from the LEP experiments (ALEPH, DELPHI, L3, and OPAL) are assumed to derive from the study of the $e^+e^- \rightarrow H^+H^-$ process. Limits from $b \rightarrow s\gamma$ decays are usually stronger in generic 2HDM models than in Supersymmetric models.

A recent combination (LEP 00B) of preliminary, unpublished results relative to data taken at LEP in the Summer of 1999 at energies up to 202 GeV gives the limit $m_{H^\pm_1} > 78.6$ GeV.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 71.5	95	ABDALLAH	02	DLPH	$E_{cm} \leq 202$ GeV
> 67.4	95	ACCIARRI	00W	L3	$E_{cm} \leq 202$ GeV
> 65.4	95	BARATE	00M	ALEP	$E_{cm} \leq 189$ GeV
> 59.5	95	ABBIENDI	99E	OPAL	$E_{cm} \leq 183$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[55] ABBIENDI	01Q	OPAL	$B \to \tau\nu_\tau X$
		[56] BARATE	01E	ALEP	$B \to \tau\nu_\tau$
>315	99	[57] GAMBINO	01	RVUE	$b \to s\gamma$
> 82.8	95	ABBIENDI	00G	OPAL	$E_{cm} \leq 189$ GeV, $B(\tau\nu) = 1$
		[58] AFFOLDER	00I	CDF	$t \to bH^+$, $H \to \tau\nu$
		[59] ABBOTT	99E	D0	$t \to bH^+$
> 56.3	95	ABREU	99R	DLPH	$E_{cm} \leq 183$ GeV
		[60] ACKERSTAFF	99D	OPAL	$\tau \to e\nu\nu$, $\mu\nu\nu$
		[61] ACCIARRI	97F	L3	$B \to \tau\nu_\tau$
		[62] AMMAR	97B	CLEO	$\tau \to \mu\nu\nu$
		[63] COARASA	97	RVUE	$B \to \tau\nu_\tau X$
		[64] GUCHAIT	97	RVUE	$t \to bH^+$, $H \to \tau\nu$
		[65] MANGANO	97	RVUE	$B_{u(c)} \to \tau\nu_\tau$
		[66] STAHL	97	RVUE	$\tau \to \mu\nu\nu$
>244	95	[67] ALAM	95	CLE2	$b \to s\gamma$
		[68] BUSKULIC	95	ALEP	$b \to \tau\nu_\tau X$

[55] ABBIENDI 01Q give a limit $\tan\beta/m_{H^+} < 0.53$ GeV^{-1} (95%CL) in Type II two-doublet models.

[56] BARATE 01E give a limit $\tan\beta/m_{H^+} < 0.40$ GeV^{-1} (90%CL) in Type II two-doublet models. An independent measurement of $B \to \tau\nu_\tau X$ gives $\tan\beta/m_{H^+} < 0.49$ GeV^{-1} (90%CL).

[57] GAMBINO 01 use the world average data in the summer of 2001 $B(b \to s\gamma) = (3.23 \pm 0.42) \times 10^{-4}$. The limit applies for Type-II two-doublet models.

[58] AFFOLDER 00I search for a charged Higgs boson in top decays with $H^+ \to \tau^+\nu$ in $p\overline{p}$ collisions at E_{cm}=1.8 TeV. The excluded mass region extends to over 120 GeV for $\tan\beta$ values above 100 and $B(\tau\nu)$=1. If $B(t \to bH^+) \gtrsim 0.6$, m_{H^+} up to 160 GeV is excluded. Updates ABE 97L.

[59] ABBOTT 99E search for a charged Higgs boson in top decays in $p\overline{p}$ collisions at E_{cm}=1.8 TeV, by comparing the observed $t\overline{t}$ cross section (extracted from the data assuming the dominant decay $t \to bW^+$) with theoretical expectation. The search is sensitive to regions of the domains $\tan\beta \lesssim 1$, $50 < m_{H^+}$(GeV) $\lesssim 120$ and $\tan\beta \gtrsim 40$, $50 < m_{H^+}$(GeV) $\lesssim 160$. See Fig. 3 for the details of the excluded region.

[60] ACKERSTAFF 99D measure the Michel parameters ρ, ξ, η, and $\xi\delta$ in leptonic τ decays from $Z \to \tau\tau$. Assuming e-μ universality, the limit $m_{H^+} > 0.97 \tan\beta$ GeV (95%CL) is obtained for two-doublet models in which only one doublet couples to leptons.

[61] ACCIARRI 97F give a limit $m_{H^+} > 2.6 \tan\beta$ GeV (90%CL) from their limit on the exclusive $B \to \tau\nu_\tau$ branching ratio.

[62] AMMAR 97B measure the Michel parameter ρ from $\tau \to e\nu\nu$ decays and assmes e/μ universality to extract the Michel η parameter from $\tau \to \mu\nu\nu$ decays. The measurement

is translated to a lower limit on m_{H^+} in a two-doublet model $m_{H^+} > 0.97 \tan\beta$ GeV (90% CL).

[63] COARASA 97 reanalyzed the constraint on the ($m_{H^\pm}$,$\tan\beta$) plane derived from the inclusive $B \rightarrow \tau\nu_\tau X$ branching ratio in GROSSMAN 95B and BUSKULIC 95. They show that the constraint is quite sensitive to supersymmetric one-loop effects.

[64] GUCHAIT 97 studies the constraints on m_{H^+} set by Tevatron data on $\ell\tau$ final states in $t\overline{t} \rightarrow (Wb)(Hb)$, $W \rightarrow \ell\nu$, $H \rightarrow \tau\nu_\tau$. See Fig. 2 for the excluded region.

[65] MANGANO 97 reconsiders the limit in ACCIARRI 97F including the effect of the potentially large $B_c \rightarrow \tau\nu_\tau$ background to $B_u \rightarrow \tau\nu_\tau$ decays. Stronger limits are obtained.

[66] STAHL 97 fit τ lifetime, leptonic branching ratios, and the Michel parameters and derive limit $m_{H^+} > 1.5 \tan\beta$ GeV (90% CL) for a two-doublet model. See also STAHL 94.

[67] ALAM 95 measure the inclusive $b \rightarrow s\gamma$ branching ratio at $\Upsilon(4S)$ and give B($b \rightarrow s\gamma$)$< 4.2 \times 10^{-4}$ (95% CL), which translates to the limit $m_{H^+} >[244 + 63/(\tan\beta)^{1.3}]$ GeV in the Type II two-doublet model. Light supersymmetric particles can invalidate this bound.

[68] BUSKULIC 95 give a limit $m_{H^+} > 1.9 \tan\beta$ GeV (90%CL) for Type-II models from $b \rightarrow \tau\nu_\tau X$ branching ratio, as proposed in GROSSMAN 94.

MASS LIMITS for $H^{\pm\pm}$ (doubly-charged Higgs boson)

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>98.5	95	[69] ABBIENDI	02C	OPAL	$E_{cm} \leq 209$ GeV
>45.6	95	[70] ACTON	92M	OPAL	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[71] GORDEEV	97	SPEC	muonium conversion
		[72] ASAKA	95	THEO	
>30.4	95	[73] ACTON	92M	OPAL	$T_3(H^{++})= +1$
>25.5	95	[73] ACTON	92M	OPAL	$T_3(H^{++})= 0$
none 6.5–36.6	95	[74] SWARTZ	90	MRK2	$T_3(H^{++}) = +1$
none 7.3–34.3	95	[74] SWARTZ	90	MRK2	$T_3(H^{++}) = 0$

[69] ABBIENDI 02C searches for pair production of $H^{++}H^{--}$, with $H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm$ (ℓ,ℓ' = e,μ,τ). the limit holds for ℓ=ℓ'=τ, and becomes stronger for other combinations of leptonic final states. To ensure the decay within the detector, the limit only applies for $g(H\ell\ell) \gtrsim 10^{-7}$.

[70] ACTON 92M limit assumes $H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm$ or $H^{\pm\pm}$ does not decay in the detector. Thus the region $g_{\ell\ell} \approx 10^{-7}$ is not excluded.

[71] GORDEEV 97 search for muonium-antimuonium conversion and find $G_{M\overline{M}}/G_F < 0.14$ (90% CL), where $G_{M\overline{M}}$ is the lepton-flavor violating effective four-fermion coupling. This limit may be converted to $m_{H^{++}} > 210$ GeV if the Yukawa copulings of H^{++} to ee and $\mu\mu$ are as large as the weak gauge coupling. For similar limits on muonium-antimuonium conversion, see the muon Particle Listings.

[72] ASAKA 95 point out that H^{++} decays dominantly to four fermions in a large region of parameter space where the limit of ACTON 92M from the search of dilepton modes does not apply.

[73] ACTON 92M from $\Delta\Gamma_Z$ <40 MeV.

[74] SWARTZ 90 assume $H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm$ (any flavor). The limits are valid for the Higgs-lepton coupling g($H\ell\ell$) $\gtrsim 7.4 \times 10^{-7}/[m_H/\text{GeV}]^{1/2}$. The limits improve somewhat for ee and $\mu\mu$ decay modes.

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