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 $SU(2)_L \times U(1)_Y$ symmetry group. Masses can be introduced by the Higgs mechanism [2]. In the simplest form of this mechanism, 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 $SU(2)_L \times U(1)_Y$ symmetry is spontaneously broken down to the electromagnetic $U(1)_{EM}$ 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. 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, $\Lambda_{GUT} \approx 10^{16}$ 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 provide masses to all charged fermions. The MSSM predicts three neutral and two charged Higgs bosons. The lightest of the neutral Higgs bosons is predicted to have its mass close to the electroweak energy scale ($\approx M_W$) [5,6].

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. 7 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 209 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 neutral Higgs boson masses up to about 117 GeV.

Higgs boson searches have also been carried out at the Tevatron $p\overline{p}$ collider. With the currently analyzed data samples, the sensitivity of the two experiments, CDF and DØ, is rather limited, but with increasing energy and sample sizes, the range of sensitivity should eventually exceed the LEP range [8]. The searches will continue later at the LHC pp collider, covering masses up to about 1 TeV [9]. If Higgs bosons are indeed discovered, the Higgs mechanism could be studied in great detail at future e^+e^- [10,11] and $\mu^+\mu^-$ colliders [12].

In order to keep this review up-to-date, some recent but unpublished results are also quoted. These are marked with (*) in the reference list and can be accessed conveniently from the public web page `http://lephiggs.web.cern.ch/LEPHIGGS/pdg2004/index.html`.

II. The Standard Model Higgs boson

The mass of the SM Higgs boson H^0 is given by $m_{H^0} = \sqrt{2\lambda}\ v$. While the vacuum expectation value of the Higgs field, $v = 247$ GeV, is fixed by the Fermi coupling, the quartic Higgs self-coupling λ is a free parameter; thus, the mass m_{H^0} is not predicted. However, arguments of self-consistency of the theory can be used to place approximate upper and lower bounds upon the mass [13]. Since for large Higgs boson masses the running coupling λ rises with energy, the theory would eventually become non-perturbative. The requirement that 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 and requiring the effective potential to be positive definite. These theoretical bounds imply that if the SM is to be self-consistent up to $\Lambda_{\rm GUT} \approx 10^{16}$ GeV, the Higgs boson mass should be within about 130 and 190 GeV. In other terms, the discovery of a Higgs boson with mass below 130 GeV would suggest the onset of new physics at a scale below $\Lambda_{\rm GUT}$.

Indirect experimental bounds for the SM Higgs boson mass are obtained from fits to precision measurements of electroweak observables, and to the measured top and $W^{\pm}$ masses. These measurements are sensitive to $\log(m_{H^0})$ through radiative corrections. The current best fit value is $m_{H^0} = 96^{+60}_{-38}$ GeV, or m_{H^0} <219 GeV at the 95% confidence level (CL) [14], which is consistent with the SM being valid up to the GUT scale.

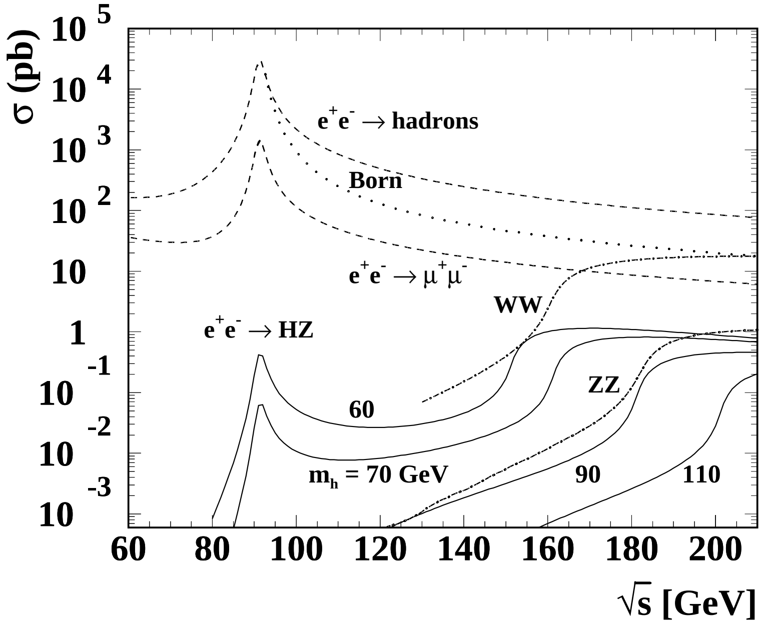
Production processes

The principal mechanism for producing the SM Higgs particle in e^+e^- collisions at LEP energies is Higgs-strahlung in the s-channel [15], $e^+e^- \to H^0Z^0$. The Z^0 boson in the final state is either virtual (LEP1), or on mass shell (LEP2). The cross section [16] $\sigma_{HZ}^{\rm SM}$ is shown in Fig. 1 (top) for the LEP energy range, together with those of the dominant background processes, $e^+e^- \to$ fermion pairs, W^+W^-, and Z^0Z^0. The SM Higgs boson can also be produced by W^+W^- and Z^0Z^0 fusion in the t-channel [17], but at LEP energies these processes have small cross sections.

At hadron colliders, the most important Higgs production processes are [18]: gluon fusion ($gg \to H^0$), Higgs production in association with a vector boson (WH^0 or ZH^0) or with a top quark pair ($t\bar{t}H^0$), and the WW fusion process giving (ppH^0 or $p\overline{p}H^0$). At the Tevatron and for masses less than about 140 GeV (where the Higgs boson mainly decays to $b\overline{b}$), the most promising discovery channels are WH^0 and ZH^0 with $H^0 \to b\overline{b}$ ($H^0 \to W^*W$ is also contributing). At the future pp collider LHC, the gluon fusion channels $gg \to H^0 \to \gamma\gamma$, WW, ZZ, the associated production channel $t\bar{t}H^0 \to t\bar{t}b\overline{b}$ and the WW fusion channel $qqH^0 \to qq\tau^+\tau^-$ are all expected to contribute. Their relative sensitivity as well as the relevance of the WH^0 and ZH^0 channels strongly depend upon the precise value of the Higgs boson mass.

Decay of the SM Higgs boson

The most relevant decays of the SM Higgs boson [16,19] are summarized in Fig. 1 (bottom). For masses below about 140 GeV, decays to fermion pairs dominate, of which the decay $H^0 \to b\overline{b}$ 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



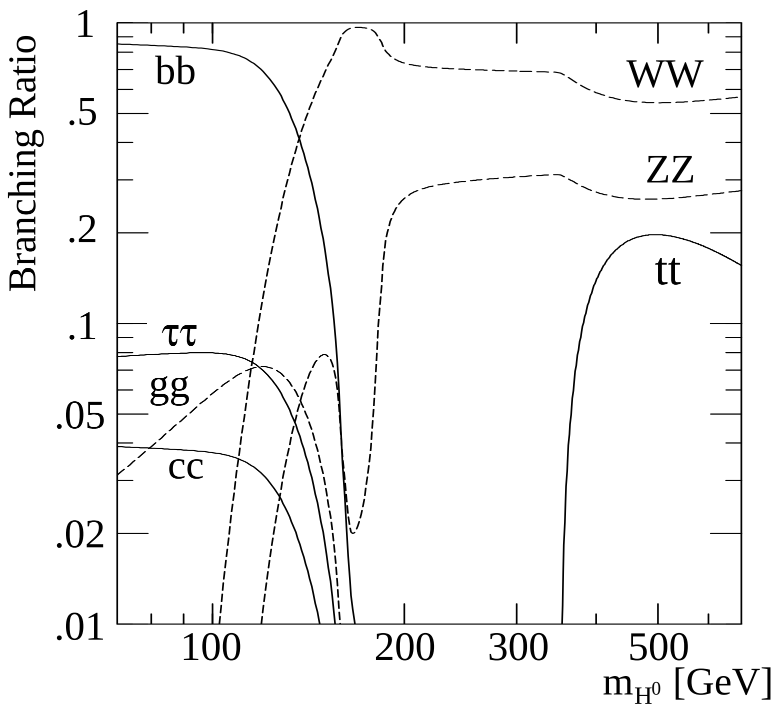


Figure 1: Cross sections, as a function of $\sqrt{s}$, for the Higgs-strahlung process in the SM for fixed values of m_{H^0} (full lines) and for other SM processes which contribute to the background; Bottom: Branching ratios for the main decay modes of the SM Higgs boson (from Ref. 10).

larger masses, the W^+W^- and Z^0Z^0 final states dominate, and the decay width rises rapidly, reaching about 1 GeV at m_{H^0}=200 GeV, and even 100 GeV at m_{H^0}=500 GeV.

Searches for the SM Higgs boson

During the LEP1 phase, the experiments ALEPH, DELPHI, L3, and OPAL analyzed over 17 million Z^0 decays, and have set lower bounds of approximately 65 GeV on the mass of the SM Higgs boson [20]. Substantial data samples have also been collected during the LEP2 phase at energies up to 209 GeV, including more than 40,000 $e^+e^- \rightarrow W^+W^-$ events. At LEP2, the composition of the background is more complex than at LEP1, due to the four-fermion processes $e^+e^- \rightarrow W^+W^-$ and Z^0Z^0, in addition to the two-fermion processes known from LEP1 (see Fig. 1 (top)). These have kinematic properties similar to the signal process (especially for $m_{H^0} \approx M_W$, M_Z), but since at LEP2 the Z^0 boson is on mass shell, constrained kinematic fits yield additional separation power. Furthermore, jets with b flavor, such as occurring in Higgs boson decays, are identified in high-precision silicon microvertex detectors.

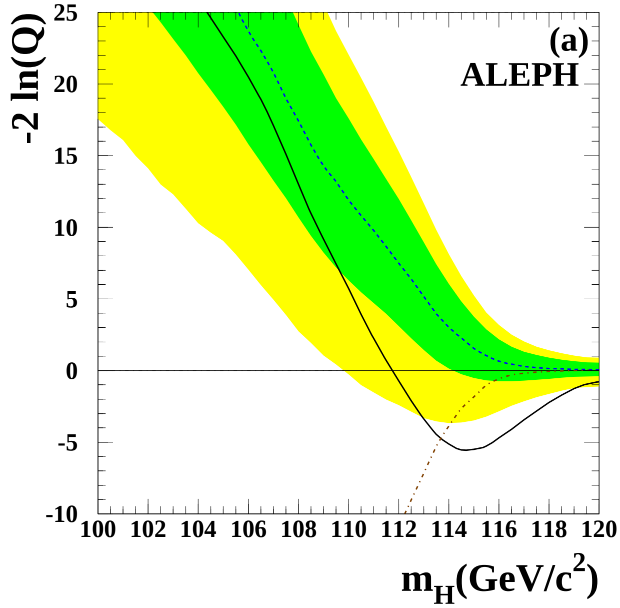
The following final states provide good sensitivity for the SM Higgs boson. (a) The most abundant, four-jet, topology is produced in the $e^+e^- \rightarrow (H^0 \rightarrow b\overline{b})(Z^0 \rightarrow q\overline{q})$ process, and occurs with a branching ratio of about 60% for a Higgs boson with 115 GeV mass. The invariant mass of two jets is close to M_Z, while the other two jets contain b flavor. (b) The missing energy topology is produced mainly in the $e^+e^- \rightarrow (H^0 \rightarrow b\overline{b})(Z^0 \rightarrow \nu\overline{\nu})$ process, and occurs with a branching ratio of about 17%. The signal has two b jets, substantial missing transverse momentum, and missing mass compatible with M_Z. (c) In the leptonic final states, $e^+e^- \rightarrow (H^0 \rightarrow b\overline{b})(Z^0 \rightarrow e^+e^-, \mu^+\mu^-)$, 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 significantly to the overall search sensitivity, since it has low background. (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 (b) and leptonic (c) final states could be used in the search for the SM Higgs boson, because of prohibitive backgrounds in the other channels; at LEP2 all four search topologies could be exploited.

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. After preselection, the combined data configuration (distribution in several discriminating variables) is compared in a frequentist approach to Monte-Carlo simulated configurations for two hypotheses: the background "b" hypothesis, and the signal plus background "$s+b$" hypothesis; in the latter case a SM Higgs boson of hypothetical mass (test-mass), m_H, is assumed in addition to the background. The ratio $Q = \mathcal{L}_{s+b}/\mathcal{L}_b$ of the corresponding likelihoods is used as test statistic. The predicted, normalized, distributions of Q (probability density functions) are integrated to obtain the p-values $1 - CL_b = 1 - \mathcal{P}_b(Q \leq Q_{\rm observed})$ and $CL_{s+b} = \mathcal{P}_{s+b}(Q \leq Q_{\rm observed})$, which measure the compatibility of the observed data configuration with the two hypotheses [21].

The searches carried out at LEP prior to the year 2000, and their combinations [22], did not reveal any evidence for the production of a SM Higgs boson. However, in the data of the year 2000, mostly at energies $\sqrt{s} > 205$ GeV, ALEPH reported an excess of about three standard deviations beyond the background prediction [23], 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 [24], L3 [25], and OPAL [26] do not show evidence for such an excess, but do not, however, exclude a 115 GeV Higgs boson. When the data of the four experiments are combined [27], the overall significance decreases to about 1.7 standard deviations. Figure 2 shows the test statistic $-2\ln Q$ for the ALEPH data and for the LEP data combined. For a test-mass $m_H = 115$ GeV, one calculates the p-values $1 - CL_b = 0.09$ for the background hypothesis and $CL_{s+b} = 0.15$ for the signal-plus-background hypothesis. From the same combination, a 95% CL lower bound of 114.4 GeV is obtained for the mass of the SM Higgs boson.

At the Tevatron, the currently published results of the CDF collaboration [28] are based on the Run I data sample of about 100 pb^{-1}. 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 and hadronic channels and the Higgs boson into a $b\overline{b}$ pair. The main source of background is from QCD processes with genuine $b\overline{b}$ pairs. The Run I data sample is too small for a discovery, but allows model-independent upper bounds to be set on the cross section for such Higgs-like event topologies. These 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, the search sensitivity will increase considerably [8]. First results from the DØ collaboration, searching for the $H^0 \to W^*W$ channel and using Run II data of about 118 pb^{-1}, have been reported [29].



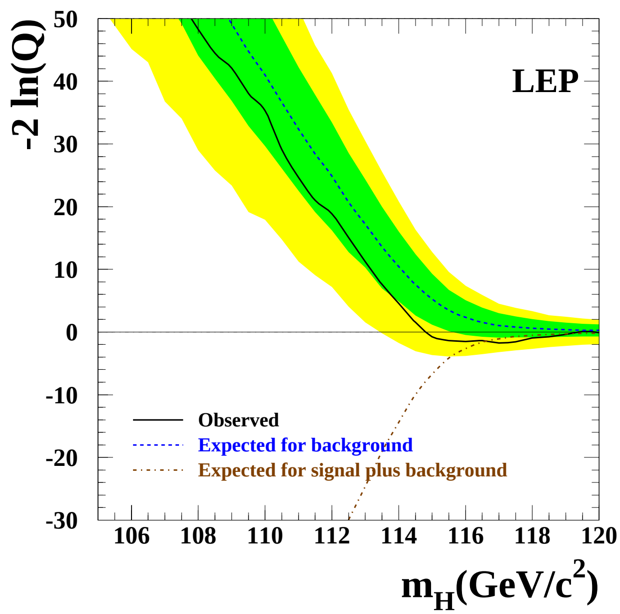


Figure 2: Observed (solid line), and expected behaviors of the test statistic $-2\ln Q$ for the background (dashed line), and the signal + background hypothesis (dash-dotted line) as a function of the test mass m_H. Top: ALEPH data alone; bottom: LEP data combined [27]. The dark and light shaded areas represent the 68% and 95% probability bands about the background expectation. See full-color version on color pages at end of book.

III. Higgs bosons in the MSSM

Most of the experimental investigations carried out so far assume CP invariance in the MSSM Higgs sector, in which case the three neutral Higgs bosons are CP eigenstates [4–6]. However, CP-violating (CPV) phases in the mechanism of soft SUSY breaking can lead to sizeable CP violation in the MSSM Higgs sector [30,31]. Such scenarios are theoretically appealing, since they provide one of the ingredients needed to explain the observed cosmic matter-antimatter asymmetry. In such models, the three neutral Higgs mass eigenstates are mixtures of CP-even and CP-odd fields. Consequently, their production and decay properties are different, and the experimental limits obtained for CP conserving (CPC) scenarios may thus be invalidated by CP-violating effects.

An important prediction of the MSSM, both CPC and CPV, is the relatively small mass of the lightest neutral scalar boson, less than about 130 GeV after radiative corrections. This prediction strongly motivated the investigations at LEP and supports future searches.

1. The CP-conserving MSSM scenario

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 of the two), one CP-odd neutral scalar A^0, and one pair of charged Higgs bosons $H^{\pm}$. At tree level, 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 diagonalizes 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 [32,33], with the largest contribution arising from the incomplete cancelation between top and scalar-top (stop) loops. The corrections affect mainly the masses in the neutral Higgs sector; they depend strongly on the top quark mass ($\sim m_t^4$), and logarithmically on the scalar-top (stop) masses. Furthermore, they involve a detailed parametrization of soft SUSY breaking and the mixing between the SUSY partners of left- and right-handed top quarks (stop mixing).

Production of neutral MSSM Higgs bosons

In e^+e^- collisions, the main production mechanisms of the neutral MSSM Higgs bosons are the Higgs-strahlung processes $e^+e^- \to h^0Z^0$, H^0Z^0 and the pair production processes $e^+e^- \to h^0A^0$, H^0A^0. Fusion processes play a marginal role at LEP energies. The cross sections for these processes can be expressed in terms of the SM Higgs boson cross section $\sigma_{HZ}^{\rm SM}$ and the parameters α and β introduced before. For the light CP-even Higgs boson h^0 the following expressions hold

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

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

with the kinematic factor

$$\overline{\lambda} = \lambda_{A^0{\rm h}^0}^{3/2} / \left[\lambda_{Z^0{\rm h}^0}^{1/2}(12M_Z^2/s + \lambda_{Z^0{\rm h}^0})\right] \tag{3}$$

and $\lambda_{ij} = [1-(m_i+m_j)^2/s][1-(m_i-m_j)^2/s]$. These Higgs-strahlung and pair production cross sections are complementary, obeying the sum rule $\sin^2(\beta-\alpha)+\cos^2(\beta-\alpha)=1$. Typically, the process $e^+e^- \to h^0Z^0$ is more abundant at small $\tan\beta$ and $e^+e^- \to h^0A^0$ at large $\tan\beta$, unless the latter is suppressed by the kinematic factor $\overline{\lambda}$. The cross sections for the heavy scalar boson H^0 are obtained by interchanging $\sin^2(\beta-\alpha)$ by $\cos^2(\beta-\alpha)$ in Eqs. 1 and 2, and replacing the index h^0 by H^0 in Eq. 3.

At the Tevatron, and over most of the MSSM parameter space, one of the CP-even neutral Higgs bosons (h^0 or H^0) couples to the vector bosons with SM-like strength. The associated production $p\overline{p} \to (h^0 \text{ or } H^0)V$ (with $V \equiv W^\pm$, Z^0), and the Yukawa process $p\overline{p} \to h^0b\overline{b}$ are the most promising search mechanisms. The gluon fusion processes $gg \to h^0$, H^0, A^0 have the highest cross section, but in these cases, only the Higgs to $\tau^+\tau^-$ decay mode is promising, since the $b\overline{b}$ decay mode is overwhelmed by QCD background.

Decay properties of neutral MSSM Higgs bosons

In the MSSM, the couplings of the neutral Higgs bosons to quarks, leptons, and gauge bosons are modified with respect to the SM couplings by factors which depend upon the angles α and β. These factors, valid at tree level, are summarized in Table 1.

The following decay features are relevant to 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 of h^0 and A^0 to $b\overline{b}$ and $\tau^+\tau^-$ pairs are preferred, with branching ratios of about 90% and

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

	"Up" fermions	"Down" fermions	Vector bosons
SM-Higgs:	1	1	1
MSSM 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

8%, while the decays to $c\overline{c}$ and gluon pairs are suppressed. Decays to $c\overline{c}$ may become important for $\tan\beta <1$. The decay $h^0 \to A^0A^0$ may be dominant if it is kinematically allowed. Other decays could imply SUSY particles such as sfermions, charginos, or invisible neutralinos, thus requiring special search strategies.

Searches for neutral Higgs bosons (CPC scenario)

The searches at LEP address the Higgs-strahlung process $e^+e^- \to h^0Z^0$ and the pair production process $e^+e^- \to h^0A^0$, and exploit the complementarity of the two cross sections. The results for h^0Z^0 are obtained by re-interpreting the SM Higgs searches, taking into account the MSSM reduction factor $\sin^2(\beta-\alpha)$. Those 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 search results are interpreted in a constrained MSSM model where universal soft SUSY breaking masses, $M_{\rm SUSY}$ and M_2, are assumed for the electroweak scale for sfermions and SU(2)×U(1) gauginos, respectively. Besides the tree-level parameters m_{A^0} and $\tan\beta$, the Higgs mixing parameter μ and trilinear Higgs-fermion coupling A_t also enter at the loop level. Most results assume a top quark mass of 174.3 GeV [34]. Furthermore, the gluino mass, entering at the two-loop level, is fixed at 800 GeV. The widths of the Higgs bosons are taken to be small compared to the experimental mass resolution, which is a valid assumption for $\tan\beta$ less than about 50.

Most interpretations are limited to specific "benchmark" scenarios [33], where some of the parameters have fixed values: $M_{\rm SUSY} = 1$ TeV, $M_2 = 200$ GeV, and $\mu = -200$ GeV. In the *no-mixing* benchmark scenario, stop mixing is put to zero by choosing $X_t \equiv A_t - \mu\cot\beta = 0$, while in the m_{h^0}-*max* benchmark scenario, $X_t = 2M_{\rm SUSY}$ is chosen. The m_{h^0}-*max* scenario is designed to maximize the allowed parameter space in the (m_{h^0}, $\tan\beta$) projection, and therefore yields the most conservative exclusion limits.

The limits from the four LEP experiments are described in Refs. [23,35,36]. Preliminary combined LEP limits [37] are shown in Fig. 3 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 if $\mathcal{O}(\alpha_t^2 m_t^2)$ corrections to $(m_{h^0})^2$ are included in the model calculation.

The neutral Higgs bosons may also be produced by Yukawa processes $e^+e^- \to f\overline{f}\phi$ with $\phi \equiv h^0$, H^0, A^0, where the Higgs particles are radiated off a massive fermion ($f \equiv b$ or $\tau^\pm$). These processes can be dominant where the "standard" processes, $e^+e^- \to h^0Z^0$ and h^0A^0, are suppressed. The corresponding enhancement factors (ratios of the $f\overline{f}h^0$ 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 $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, and $\tau^+\tau^-\tau^+\tau^-$ final states [38]. Regions of low mass and high enhancement factors are excluded by these searches. The CDF collaboration has searched for the Yukawa process $p\overline{p} \to b\overline{b}\ \phi \to b\overline{b}b\overline{b}$ [39]; the domains excluded, at large $\tan\beta$, are indicated in Fig. 3 along with the limits from LEP.

2. The CP-violating MSSM scenario

Within the SM, the size of CP violation is insufficient to drive the cosmological baryon asymmetry. In the MSSM, however, while the Higgs potential is invariant under the CP transformation at tree level, CP symmetry could be broken substantially by radiative corrections, especially by contributions from third generation scalar-quarks [31]. Such a scenario has recently been investigated by the OPAL Collaboration [36].

In the CPV MSSM scenario, the three neutral Higgs eigenstates H_i $(i = 1, 2, 3)$ do not have well defined CP quantum numbers; each of them can thus be produced by Higgs-strahlung, $e^+e^- \to H_i Z^0$, and in pairs, $e^+e^- \to H_i H_j$ $(i \neq j)$. For wide ranges of the model parameters, the lightest neutral Higgs boson H_1 has a predicted mass that is accessible at LEP, but it may decouple from the Z^0 boson. On the other hand, the second- and third-lightest Higgs bosons H_2 and H_3 may be either out of reach, or may also have small cross sections. Thus, the searches in the CPV MSSM scenario are experimentally more challenging than in the CPC scenario.

The cross section for the Higgs-strahlung and pair production processes are given by [31]

$$\sigma_{H_i Z^0} = g^2_{H_i ZZ}\ \sigma^{\rm SM}_{HZ} \tag{4}$$

$$\sigma_{H_i H_j} = g^2_{H_i H_j Z}\ \overline{\lambda}\ \sigma^{\rm SM}_{HZ} \tag{5}$$

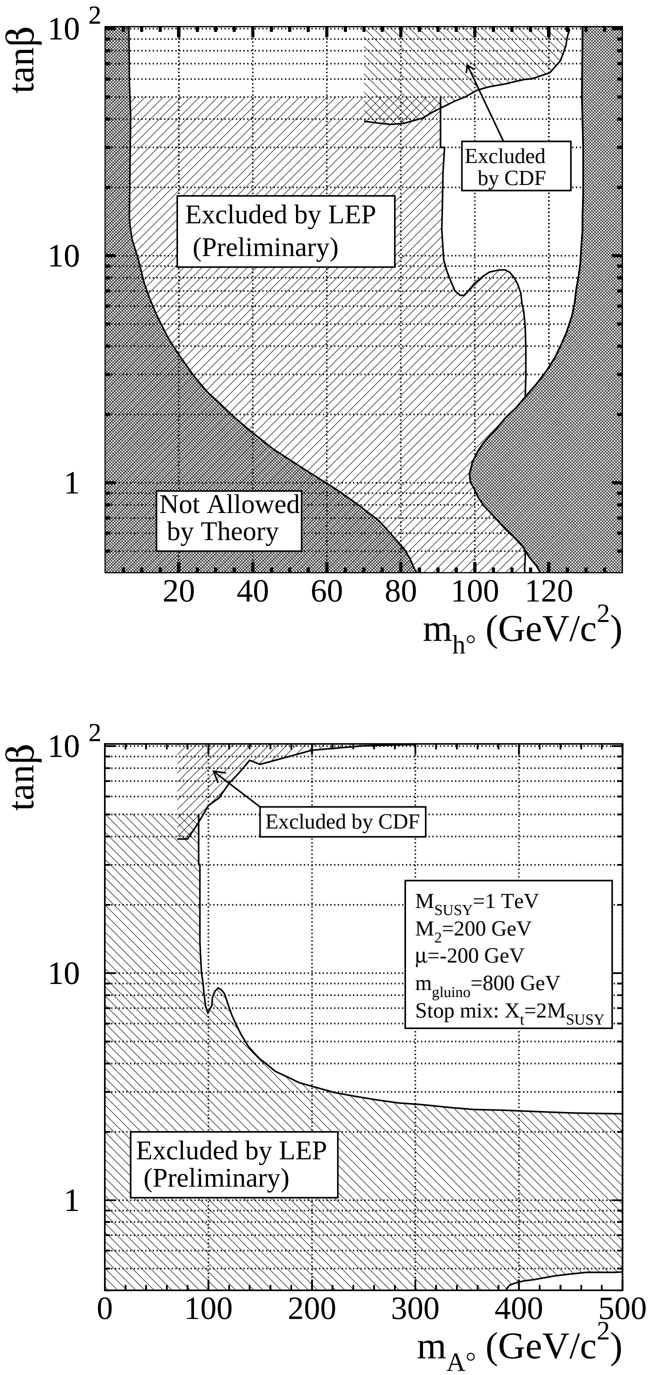


Figure 3: The 95% CL bounds on m_{h^0}, m_{A^0} and $\tan\beta$ for the m_{h^0}-*max* benchmark scenario, from LEP [37]. The exclusions at large $\tan\beta$ from CDF [39] are also indicated.

(in the expression of $\overline{\lambda}$, Eq. 3, the indices h^0 and A^0 have to be replaced by H_1 and H_2). The couplings

$$g_{H_iZZ} = \cos\beta\mathcal{O}_{1i} + \sin\beta\mathcal{O}_{2i} \tag{6}$$

$$\begin{aligned} g_{H_iH_jZ} = {} & \mathcal{O}_{3i}(\cos\beta\mathcal{O}_{2j} - \sin\beta\mathcal{O}_{1j}) \\ & - \mathcal{O}_{3j}(\cos\beta\mathcal{O}_{2i} - \sin\beta\mathcal{O}_{1i}) \end{aligned} \tag{7}$$

obey sum rules which, similarly to the CPC case, express the complementarity of the two cross sections. The orthogonal matrix $\mathcal{O}_{ij}$ $(i,j = 1,2,3)$ relating the weak CP eigenstates to the mass eigenstates has non-zero off-diagonal elements,

$$\mathcal{M}^2_{ij} \sim m_t^4 \cdot \mathrm{Im}(\mu A_t)/M^2_{\mathrm{SUSY}} \ ; \tag{8}$$

their size is a measure for CP-violating effects in the production processes.

Regarding the decay properties, the lightest mass eigenstate, H_1, predominantly decays to $b\overline{b}$ if kinematically allowed, with only a small fraction decaying to $\tau^+\tau^-$. The second-lightest Higgs boson, H_2, decays predominantly to H_1H_1 when kinematically allowed, otherwise preferentially to $b\overline{b}$.

The OPAL search [36] is performed for a number of variants of the CPX benchmark scenario [40], where the parameters are chosen in such a way as to maximize the off-diagonal elements $\mathcal{M}^2_{ij}$, and thereby enhance the phenomenological differences with respect to the CPC scenario. This is obtained typically for small M_{SUSY} (*e.g.*, 500 GeV) and large μ (up to 4 TeV), and when the CPV phases related to $A_{t,b}$ and $m_{\widetilde{g}}$ are put to their maximal values. The precise choice of the top quark mass is also an issue. Figure 4 shows the preliminary OPAL exclusions in the $(m_{H_1}, \tan\beta)$ plane [36]. Values of $\tan\beta$ less than about

3 are excluded at the 95% CL, but no absolute limit can be set today for the mass of H_1 .

IV. Charged Higgs bosons

Charged Higgs bosons are predicted in models with two Higgs field doublets (2HDM), thus also in the MSSM [4,5]. 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 general 2HDM case. The searches conducted at LEP and at the Tevatron are, therefore, interpreted primarily in the general 2HDM framework.

Searches for charged Higgs bosons at LEP

In e^+e^- collisions, charged Higgs bosons are expected to be pair-produced via s-channel exchange of a photon or a Z^0 boson [5,19]. In the 2HDM framework, the couplings are specified by the electric charge and the weak mixing angle θ_W, and the cross section only depends on the mass $m_{H^\pm}$ at tree level. Charged Higgs bosons decay preferentially to heavy particles, but the precise branching ratios are model dependent. In 2HDM of "type 2,"* and for masses which are accessible at LEP energies, the decays $H^+ \to c\overline{s}$ and $\tau^+\nu$ dominate. The final states $H^+H^- \to (c\overline{s})(\overline{c}s)$, $(\tau^+\nu_\tau)(\tau^-\overline{\nu}_\tau)$, and $(c\overline{s})(\tau^-\overline{\nu}_\tau)+(\overline{c}s)(\tau^+\nu_\tau)$ are therefore considered, and the results are presented with the $H^+ \to \tau^+\nu$ decay branching ratio as a free parameter.

At LEP2 energies, the background process $e^+e^- \to W^+W^-$ constrains the search sensitivity essentially to $m_{H^\pm}$ less than

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* In the 2HDM of "type 2," the two Higgs fields couple separately to "up" and "down" type fermions; in the 2HDM of "type 1," one field couples to all fermions while the other field is decoupled.

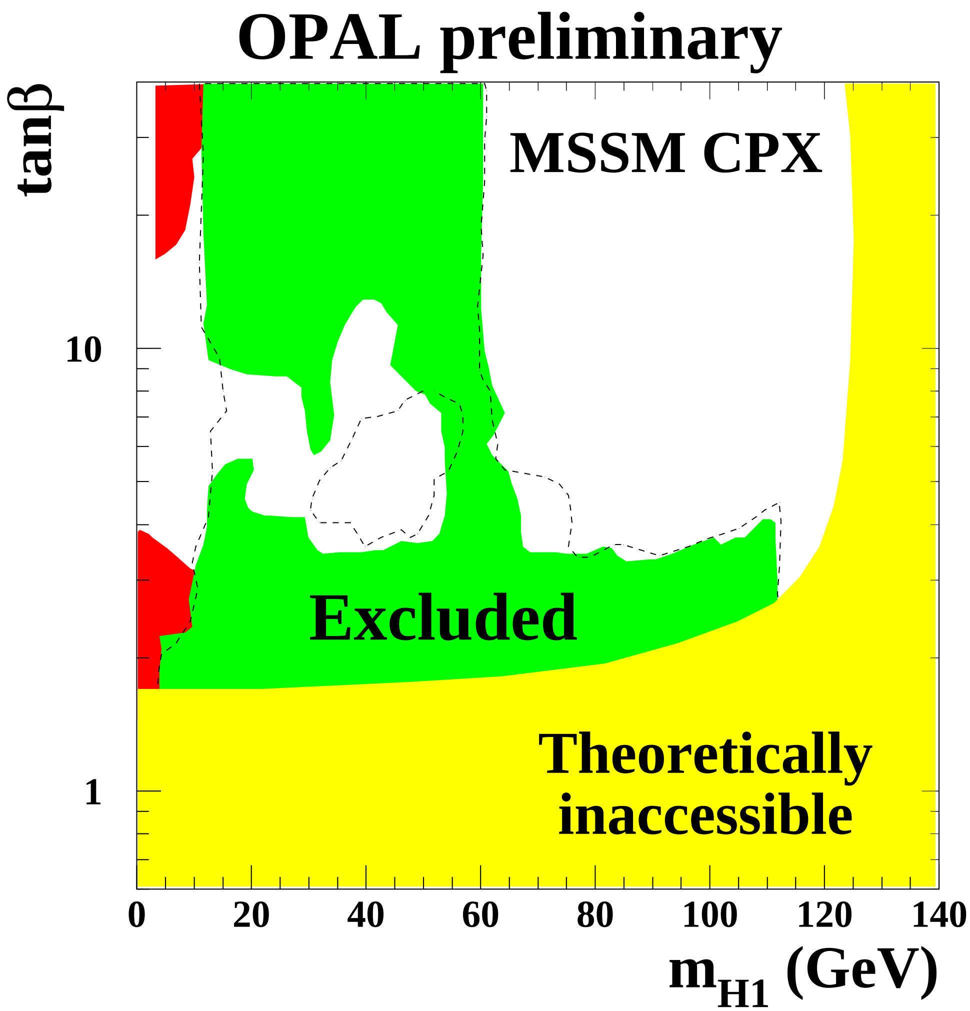

Figure 4: The 95% CL bounds on m_{H_1} and $\tan\beta$ in the CPX MSSM scenario with $\mu = 2$ TeV and $M_{\rm SUSY} = 500$ GeV, from a preliminary OPAL analysis [36]. The shaded areas are excluded either by the model or by the experiment. The areas delimited by the dashed lines are expected to be excluded on the basis of Monte Carlo simulations. The top mass is fixed to 174.3 GeV. See full-color version on color pages at end of book.

M_W. The searches of the four LEP experiments are described in Ref. 41. A preliminary combination [42] resulted in a general 2HDM ("type 2") bound of $m_{H^\pm} >$78.6 GeV (95% CL), which is valid for arbitrary $H^+ \to \tau^+\nu$ branching ratio.

In the 2HDM of "type 1" [43], and if the CP-odd neutral Higgs boson A^0 is light (which is not excluded in the general 2HDM case), the decay $H^\pm \to W^{(\pm *)}A^0$ may be predominant for masses of interest at LEP. To cover this eventuality, the search of the DELPHI Collaboration is extended to this decay mode [44].

Searches for charged Higgs bosons at the Tevatron

In $p\overline{p}$ collisions at Tevatron energies, charged Higgs bosons with mass less than $m_t - m_b$ can be produced in the decay of the top quark. The decay $t \to bH^+$ would then compete with the SM process $t \to bW^+$, and the relative rate would depend on the value of $\tan\beta$. In the 2HDM of "type 2," the decay to charged Higgs bosons could have a detectable rate for $\tan\beta$ larger than 30, or for $\tan\beta$ less than one.

The DØ Collaboration adopted an indirect "disappearance technique" optimized for the detection of $t \to bW^+$, and a direct search for $t \to bH^+ \to b\tau^+\nu_\tau$ [45]. The CDF Collaboration also reported an indirect approach [46], in which the rate of dileptons and lepton+jets in top quark decays was compared to the SM prediction, and on a direct search for $t \to bH^+$ [47]. The results from the Tevatron are summarized in Fig. 5, together with the exclusion obtained at LEP. The Tevatron limits are subject to potentially large theoretical uncertainties [48].

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 exchange [49], while

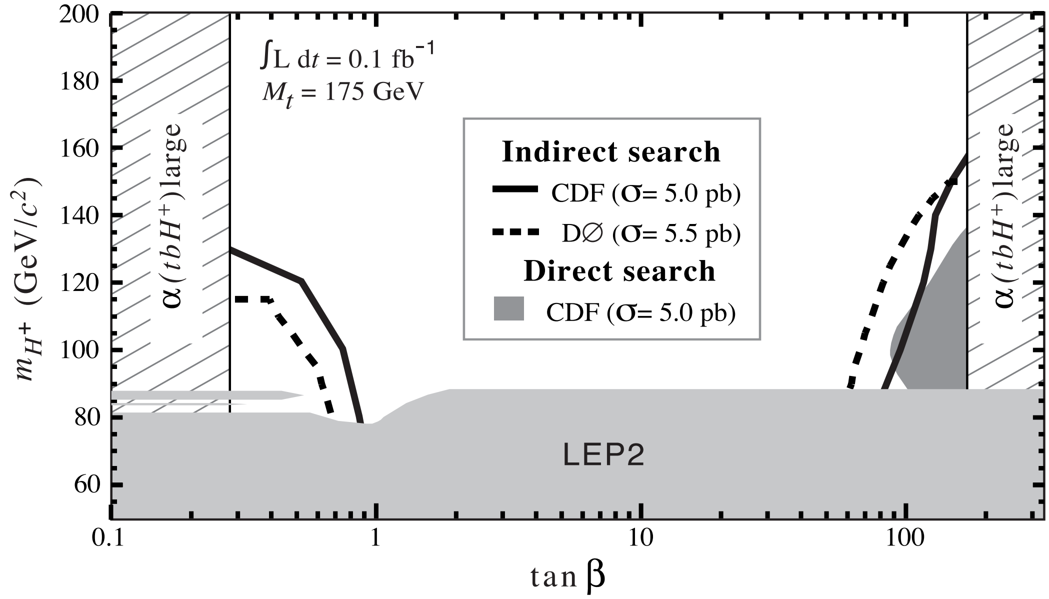

Figure 5: Summary of the 95% CL exclusions in the $(m_{H^+}, \tan\beta)$ plane from DØ [45] and CDF [47], using various indirect and direct observation techniques (the regions below the curves are excluded). The two experiments use slightly different theoretical $t\bar{t}$ cross sections, as indicated. The shaded 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 [42]. See full-color version on color pages at end of book.

in the 2HDM of "type 2," the branching ratio is altered by contributions from the exchange of charged Higgs bosons [50]. The current experimental value, obtained from combining the measurements of CLEO, BELLE, and ALEPH [51], 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 may be invalidated by anomalous couplings or, in SUSY models, by sparticle loops.

Doubly-charged Higgs bosons

Higgs bosons with double electric charge, $H^{\pm\pm}$, are predicted, for example, by models with additional triplet scalar fields or left-right symmetric models [5,52]. It has been emphasized that the see-saw mechanism could lead to doubly-charged Higgs bosons with masses accessible to current and future colliders [53]. Searches were performed at LEP for the pair-production process $Z^0 \to H^{++}H^{--}$ with four prompt leptons in the final state [54–56]. Lower mass bounds between 95 GeV and 100 GeV were obtained for left-right symmetric models (the exact limits depend on the lepton flavors). Doubly-charged Higgs bosons were also searched in single production [57]. Furthermore, if such particles existed, they would affect the Bhabha scattering cross-section and forward-backward asymmetry via t-channel exchange. The absence of a significant deviation from the SM prediction puts constraints on the Yukawa coupling of $H^{\pm\pm}$ to electrons for Higgs masses which reach into the TeV range [56,57].

V. Model extensions

The addition of a singlet scalar field to the CP-conserving MSSM [58] 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 has reinterpreted their searches for neutral Higgs bosons to constrain such models [59].

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 [60]. 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. Results from the LEP experiments can be found in Refs. [23,61]. Some 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 [62].

Most of the searches for the processes $e^+e^- \to h^0Z^0$ and h^0A^0, which have been discussed in the context of the CPC MSSM, rely on the experimental signature of Higgs bosons decaying into $b\overline{b}$. However, in the general 2HDM case, decays to non-$b\overline{b}$ final states may be strongly enhanced. Recently flavor-independent searches have been reported at LEP which do not require b tagging [63], and a preliminary combination has been performed [64]. In conjunction with the b-flavor sensitive searches, large domains of the general 2HDM parameter space of "type 2" could be excluded [65].

Photonic final states from the processes $e^+e^- \to Z^0\ /\gamma^* \to H^0\gamma$ and $H^0 \to \gamma\gamma$, do not occur in the SM at tree level, but may have a low rate due to $W^\pm$ and top quark loops [66]. Additional loops, for example, from SUSY particles, would increase the rates only slightly [67], but models with anomalous couplings predict enhancements by orders of magnitude. Searches for the processes $e^+e^- \to (H^0 \to b\overline{b})\gamma$, $(H^0 \to \gamma\gamma)q\overline{q}$, and $(H^0 \to \gamma\gamma)\gamma$ have been used to set model-independent limits on such anomalous couplings, and to constrain the very specific "fermiophobic" 2HDM of "type 1" [68], which also predicts an enhanced $h^0 \to \gamma\gamma$ rate. The LEP searches are described in Ref. 69. In a preliminary combination [70], a fermiophobic Higgs boson with mass less than 108.2 GeV (95% CL) has been excluded. Limits of about 80 GeV are obtained at the Tevatron [71]. Along with the photonic decay, the 2HDM of "type 1" also predicts an enhanced rate for the decays $h^0 \to W^*W$ and $Z^{0*}Z^0$. This possibility has been addressed by the L3 Collaboration [72].

The OPAL Collaboration has performed a decay-mode independent search for the Bjorken process $e^+e^- \to \ S^0Z^0$ [73], where S^0 denotes a generic scalar particle. The search is based on studies of the recoil mass spectrum in events with $Z^0 \to e^+e^-$ and $Z^0 \to \mu^+\mu^-$ decays, and on the final states $(Z^0 \to \nu\overline{\nu})(S^0 \to e^+e^-$ or photons), and produces upper bounds for the cross section for a broad range of S^0 masses between 10^{-6} GeV to 100 GeV.

VI. Prospects

The LEP collider stopped producing data in November 2000. At the Tevatron, Run II started in 2001. Performance studies suggest [8] that collecting data samples in excess of 2 fb^{-1} per experiment would extend the combined sensitivity of CDF and DØ beyond the LEP reach; with 4 fb^{-1} (9 fb^{-1}) per experiment, the Tevatron should be able to exclude (detect at the 3σ level) the Higgs boson up to about 130 GeV mass. Such data samples would also provide sensitivity to MSSM Higgs bosons in large domains of the parameter space.

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 [9]. The discovery of the SM Higgs boson will be possible over the mass range between about 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 of the 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 [11]. One of the prime goals would be to extend the precision measurements, which are 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 [74]. At a future $\mu^+\mu^-$ collider, the Higgs bosons can be generated as s-channel resonances [12]. 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.

Models are emerging which propose solutions to the electroweak scale hierarchy problem without introducing SUSY. The "little Higgs model" [75] proposes an additional set of heavy gauge bosons with Higgs-gauge couplings tuned in such a way that the quadratic divergences induced by the SM gauge boson loops are cancelled. Among the strong signatures of this model, there are the new gauge bosons, but there is also a doubly charged Higgs boson with mass in the TeV range, decaying to W^+W^+. These predictions can be tested at future colliders. Alternatively, models with extra space dimensions [76] propose a natural way for avoiding the scale hierarchy problem. In this class of models, the Planck scale looses its fundamental character and becomes merely an effective scale in 3-dimensional space. The model predicts a light Higgs-like particle, the radion, which differs from the Higgs boson in that it couples more strongly to gluons. A first search for the radion in LEP data, conducted by OPAL, gave negative results [77].

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 [78] expected in theories with dynamical symmetry breaking [79].

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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 202 GeV, and weaker limits obtained from other sources, have been superseded by the most recent data of LEP. They have been removed from this comiplation, and are documented in previous editions 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.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>114.1	95	[1] ABDALLAH	04	DLPH	$E_{cm} \leq$ 209 GeV
>112.7	95	[1] ABBIENDI	03B	OPAL	$E_{cm} \leq$ 209 GeV
>114.4	95	[1,2] HEISTER	03D	LEP	$E_{cm} \leq$ 209 GeV
>111.5	95	[1,3] HEISTER	02	ALEP	$E_{cm} \leq$ 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. • • •					
		[4] ABAZOV	01E	D0	$p\overline{p} \rightarrow H^0 W X$, $H^0 Z X$
		[5] ABE	98T	CDF	$p\overline{p} \rightarrow H^0 W X$, $H^0 Z X$

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

[2] Combination of the results of all LEP experiments.

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

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

[5] 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 $W(Z) \rightarrow q\overline{q}^{(\prime)}$, $H^0 \rightarrow b\overline{b}$. The results are combined with the search in ABE 97W, resulting in the cross-section limit $\sigma(H^0 + W/Z)\cdot$B$(H^0 \rightarrow b\overline{b})$<(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 02,) although we do not include it in the Listings or Tables: m_H= 81^{+52}_{-33} GeV. This is obtained from a fit to LEP, SLD, W mass, top mass, and neutrino scattering data available in the Summer of 2002, with $\Delta\alpha^{(5)}_{\rm had}(m_Z)$= 0.0276 ± 0.0036. The 95%CL limit is 193 GeV.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[6] CHANOWITZ	02	RVUE	
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	

[6] CHANOWITZ 02 studies the impact for the prediction of the Higgs mass of two 3σ anomalies in the SM fits to electroweak data. It argues that the Higgs mass limit should not be trusted whether the anomalies originate from new physics or from systematic effects.

[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, $1/\alpha(m^2_Z)$ = 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 $m_t = 175 \pm 6$ GeV from CDF/DØ . The fit yields $m_t = 172 \pm 6$ 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^0_1 and H^0_2, where we define $m_{H^0_1} < m_{H^0_2}$], a pseudoscalar (A^0), and a charged Higgs pair ($H^{\pm}$). H^0_1 and H^0_2 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 $m_{H^0_1} \leq m_Z$, $m_{H^0_2} \geq m_Z$, $m_{A^0} \geq m_{H^0_1}$, 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 $e^+e^- \to H^0_1 Z^0$ in the channels used for the Standard Model Higgs searches and $e^+e^- \to H^0_1 A^0$ 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 $m_{H^0_1}$. 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 $m_{H^0_1} \lesssim 45$ 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 earlier editions of this Review. Unless otherwise stated, the following results assume no invisible H^0_1 or A^0 decays.

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

VALUE (GeV)	CL%		DOCUMENT ID		TECN	COMMENT
> 89.7	95	[19,20]	ABDALLAH	04	DLPH	$E_{cm} \leq 209$ GeV, tan$\beta > 0.4$
> 86.0	95	[19,21]	ACHARD	02H	L3	$E_{cm} \leq 209$ GeV, tan$\beta > 0.4$
> 89.8	95	[19,22]	HEISTER	02	ALEP	$E_{cm} \leq 209$ GeV, tan$\beta > 0.5$
>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. • • •						
		[25]	ABBIENDI	03G	OPAL	$H_1^0 \rightarrow A^0 A^0$

[19] Search for $e^+e^- \rightarrow H_1^0 A^0$ in the final states $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$, and $e^+e^- \rightarrow H_1^0 Z$. 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 the so-called "m_h-max scenario" (CARENA 99B).

[20] This limit applies also in the no-mixing scenario. Furthermore, ABDALLAH 04 excludes the range $0.54 <$ tan$\beta < 2.36$. The limit improves in the region tan$\beta < 6$ (see Fig. 28). Limits for $\mu = 1$ TeV are given in Fig. 30.

[21] ACHARD 02H also search for the final state $H_1^0 Z \rightarrow 2A^0 q\overline{q}$, $A^0 \rightarrow q\overline{q}$. In addition, the MSSM parameter set in the "large-μ" and "no-mixing" scenarios are examined.

[22] HEISTER 02 excludes the range $0.7 <$tan$\beta < 2.3$. A wider range is excluded with different stop mixing assumptions. Updates BARATE 01C.

[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 $e^+e^- \rightarrow H_1^0 A^0$ in the final states $b\overline{b}b\overline{b}$, $b\overline{b}\tau^+\tau^-$, and $A^0 A^0 A^0 \rightarrow b\overline{b}b\overline{b}b\overline{b}$, and $e^+e^- \rightarrow H_1^0 Z$. 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.

[25] ABBIENDI 03G search for $e^+e^- \rightarrow H_1^0 Z$ followed by $H_1^0 \rightarrow A^0 A^0$, $A^0 \rightarrow c\overline{c}$, gg, or $\tau^+\tau^-$. In the no-mixing scenario, the region $m_{H_1^0}$ = 45-85 GeV and m_{A^0} = 2-9.5 GeV is excluded at 95% CL.

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

VALUE (GeV)	CL%		DOCUMENT ID		TECN	COMMENT
> 90.4	95	[26,27]	ABDALLAH	04	DLPH	$E_{cm} \leq 209$ GeV, tan$\beta > 0.4$
> 86.5	95	[26,28]	ACHARD	02H	L3	$E_{cm} \leq 209$ GeV, tan$\beta > 0.4$
> 90.1	95	[26,29]	HEISTER	02	ALEP	$E_{cm} \leq 209$ GeV, tan$\beta > 0.5$
>100	95	[30]	AFFOLDER	01D	CDF	$p\overline{p} \rightarrow b\overline{b}A^0$, tan$\beta \gtrsim 55$
> 76.5	95	[31]	ABBIENDI	00F	OPAL	$E_{cm} \leq 189$ GeV, tan$\beta > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
		[32]	ABBIENDI	03G	OPAL	$H_1^0 \rightarrow A^0 A^0$
		[33]	AKEROYD	02	RVUE	

[26] 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 the so-called "m_h-max scenario" (CARENA 99B).

[27] This limit applies also in the no-mixing scenario. Furthermore, ABDALLAH 04 excludes the range 0.54 < tanβ < 2.36. The limit improves in the region tanβ < 6 (see Fig. 28). Limits for $\mu = 1$ TeV are given in Fig. 30.

[28] ACHARD 02H also search for the final state $H^0_1 Z \rightarrow 2A^0 q\overline{q}$, $A^0 \rightarrow q\overline{q}$. In addition, the MSSM parameter set in the "large-μ" and "no-mixing" scenarios are examined.

[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] 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.

[31] 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 $A^0 A^0 A^0 \rightarrow b\overline{b}b\overline{b}b\overline{b}$, 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.

[32] ABBIENDI 03G search for $e^+ e^- \rightarrow H^0_1 Z$ followed by $H^0_1 \rightarrow A^0 A^0$, $A^0 \rightarrow c\overline{c}$, gg, or $\tau^+\tau^-$. In the no-mixing scenario, the region $m_{H^0_1}$ = 45-85 GeV and m_{A^0} = 2-9.5 GeV is excluded at 95% CL.

[33] AKEROYD 02 examine the possibility of a light A^0 with tanβ <1. Electroweak measurements are found to be inconsistent with such a scenario.

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. • • •					
		[34] ABDALLAH	04	DLPH	$H^0 V V$ couplings
		[35] ABBIENDI	03F	OPAL	$e^+ e^- \rightarrow H^0 Z$, $H^0 \rightarrow$ any
		[36] ABBIENDI	03G	OPAL	$H^0_1 \rightarrow A^0 A^0$
>107	95	[37] ACHARD	03C	L3	$H^0 \rightarrow W W^*, Z Z^*, \gamma\gamma$
		[38] ABBIENDI	02D	OPAL	$e^+ e^- \rightarrow b\overline{b}H$
>105.5	95	[39,40] ABBIENDI	02F	OPAL	$H^0_1 \rightarrow \gamma\gamma$
>105.4	95	[41] ACHARD	02C	L3	$H^0_1 \rightarrow \gamma\gamma$
>114.1	95	[42] HEISTER	02	ALEP	Invisible H^0, $E_{cm} \leq 209$ GeV
>105.4	95	[39,43] HEISTER	02L	ALEP	$H^0_1 \rightarrow \gamma\gamma$

>109.1	95	[44] HEISTER	02M	ALEP	$H^0 \to$ 2 jets or $\tau^+\tau^-$
none 1–44	95	[45] ABBIENDI	01E	OPAL	H_1^0, Type-II model
none 12–56	95	[45] ABBIENDI	01E	OPAL	A^0, Type-II model
>107	95	[46] ABREU	01F	DLPH	$H_1^0 \to \gamma\gamma$
> 98	95	[47] AFFOLDER	01H	CDF	$p\overline{p} \to H^0 W/Z$, $H^0 \to \gamma\gamma$
>106.4	95	[42] BARATE	01C	ALEP	Invisible H^0, $E_{cm} \leq$ 202 GeV
> 89.2	95	[48] ACCIARRI	00M	L3	Invisible H^0
		[49] ACCIARRI	00R	L3	$e^+e^- \to H^0\gamma$ and/or $H^0 \to \gamma\gamma$
		[50] ACCIARRI	00R	L3	$e^+e^- \to e^+e^- H^0$
> 94.9	95	[51] ACCIARRI	00S	L3	$e^+e^- \to H^0 Z$, $H^0 \to \gamma\gamma$
>100.7	95	[52] BARATE	00L	ALEP	$e^+e^- \to H^0 Z$, $H^0 \to \gamma\gamma$
> 68.0	95	[53] ABBIENDI	99E	OPAL	$\tan\beta > 1$
> 96.2	95	[54] ABBIENDI	99O	OPAL	$e^+e^- \to H^0 Z$, $H^0 \to \gamma\gamma$
> 78.5	95	[55] ABBOTT	99B	D0	$p\overline{p} \to H^0 W/Z$, $H^0 \to \gamma\gamma$
		[56] ABREU	99P	DLPH	$e^+e^- \to H^0\gamma$ and/or $H^0 \to \gamma\gamma$
> 76.1	95	[57] ABREU	99Q	DLPH	Invisible H^0
		[58] GONZALEZ-G..	98B	RVUE	Anomalous coupling
		[59] KRAWCZYK	97	RVUE	$(g-2)_\mu$
		[60] ALEXANDER	96H	OPAL	$Z \to H^0\gamma$
		[61] ABREU	95H	DLPH	$Z \to H^0 Z^*$, $H^0 A^0$
		[62] PICH	92	RVUE	Very light Higgs

[34] ABDALLAH 04 consider the full combined LEP and LEP2 datasets to set limits on the Higgs coupling to W or Z bosons, assuming SM decays of the Higgs. Results in Fig. 26.

[35] ABBIENDI 03F search for $H^0 \to$ anything in $e^+e^- \to H^0 Z$, using the recoil mass spectrum of $Z \to e^+e^-$ or $\mu^+\mu^-$. In addition, it searched for $Z \to \nu\overline{\nu}$ and $H^0 \to e^+e^-$ or photons. Scenarios with large width or continuum H^0 mass distribution are considered. See their Figs. 11–14 for the results.

[36] ABBIENDI 03G search for $e^+e^- \to H_1^0 Z$ followed by $H_1^0 \to A^0 A^0$, $A^0 \to c\overline{c}$, gg, or $\tau^+\tau^-$ in the region $m_{H_1^0}$ = 45-86 GeV and m_{A^0} = 2-11 GeV. See their Fig. 7 for the limits.

[37] ACHARD 03C search for $e^+e^- \to Z H^0$ followed by $H^0 \to W W^*$ or $Z Z^*$ at E_{cm}= 200-209 GeV and combine with the ACHARD 02C result. The limit is for a H^0 with SM production cross section and B($H^0 \to f\overline{f}$) = 0 for all f. For B($H^0 \to W W^*$) + B($H^0 \to Z Z^*$) = 1, m_{H^0} > 108.1 GeV is obtained. See fig. 6 for the limits under different BR assumptions.

[38] ABBIENDI 02D search for $Z \to b\overline{b} H_1^0$ and $b\overline{b} A^0$ with $H_1^0 / A^0 \to \tau^+\tau^-$, in the range $4 < m_H < 12$ GeV. See their Fig. 8 for limits on the Yukawa coupling.

[39] Search for associated production of a $\gamma\gamma$ resonance with a Z boson, followed by $Z \to q\overline{q}$, $\ell^+\ell^-$, or $\nu\overline{\nu}$, at $E_{cm} \leq$ 209 GeV. The limit is for a H^0 with SM production cross section and B($H^0 \to f\overline{f}$)=0 for all fermions f.

[40] For B($H^0 \to \gamma\gamma$)=1, m_{H^0} >117 GeV is obtained.

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

[42] 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.

[43] For B($H^0 \rightarrow \gamma\gamma$)=1, $m_{H^0} > 113.1$ GeV is obtained.

[44] HEISTER 02M search for $e^+e^- \rightarrow H^0 Z$, assuming that H^0 decays to $q\overline{q}$, gg, or $\tau^+\tau^-$ only. The limit assumes SM production cross section.

[45] 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_1^0, $A^0 \rightarrow q\overline{q}$, gg are searched for. See their Figs. 15,16 for excluded regions.

[46] 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.

[47] 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.

[48] ACCIARRI 00M search for $e^+e^- \rightarrow ZH^0$ 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.

[49] 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.

[50] 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.

[51] 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($H \rightarrow \gamma\gamma$)$\cdot\sigma(e^+e^- \rightarrow Hf\overline{f})/\sigma(e^+e^- \rightarrow Hf\overline{f})$ (SM).

[52] 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($H \rightarrow \gamma\gamma$)$\cdot\sigma(e^+e^- \rightarrow Hf\overline{f})/\sigma(e^+e^- \rightarrow Hf\overline{f})$ (SM).

[53] 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.

[54] 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.

[55] 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.

[56] 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.

[57] 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.

[58] 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.

[59] 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.

[60] 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.

[61] 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.

[62] 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 $m_{H_1^\pm} > 78.6$ GeV.

VALUE (GeV)	CL%		DOCUMENT ID		TECN	COMMENT
> 71.5	95		ABDALLAH	02	DLPH	$E_{cm} \le 202$ GeV
> 79.3	95		HEISTER	02P	ALEP	$E_{cm} \le 209$ GeV
> 67.4	95		ACCIARRI	00W	L3	$E_{cm} \le 202$ GeV
> 59.5	95		ABBIENDI	99E	OPAL	$E_{cm} \le 183$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
		63	ABBIENDI	03	OPAL	$\tau \to \mu \overline{\nu} \nu$, $e \overline{\nu} \nu$
		64	ABAZOV	02B	D0	$t \to bH^+$, $H \to \tau \nu$
		65	BORZUMATI	02	RVUE	
		66	ABBIENDI	01Q	OPAL	$B \to \tau \nu_\tau X$
		67	BARATE	01E	ALEP	$B \to \tau \nu_\tau$
>315	99	68	GAMBINO	01	RVUE	$b \to s \gamma$
> 82.8	95		ABBIENDI	00G	OPAL	$E_{cm} \le 189$ GeV, B$(\tau\nu) = 1$
		69	AFFOLDER	00I	CDF	$t \to bH^+$, $H \to \tau \nu$
		70	ABBOTT	99E	D0	$t \to bH^+$
> 56.3	95		ABREU	99R	DLPH	$E_{cm} \le 183$ GeV
		71	ACKERSTAFF	99D	OPAL	$\tau \to e \nu \nu$, $\mu \nu \nu$
		72	ACCIARRI	97F	L3	$B \to \tau \nu_\tau$
		73	AMMAR	97B	CLEO	$\tau \to \mu \nu \nu$
		74	COARASA	97	RVUE	$B \to \tau \nu_\tau X$
		75	GUCHAIT	97	RVUE	$t \to bH^+$, $H \to \tau \nu$
		76	MANGANO	97	RVUE	$B_{u(c)} \to \tau \nu_\tau$
		77	STAHL	97	RVUE	$\tau \to \mu \nu \nu$
>244	95	78	ALAM	95	CLE2	$b \to s \gamma$
		79	BUSKULIC	95	ALEP	$b \to \tau \nu_\tau X$

[63] ABBIENDI 03 give a limit $m_{H^+} > 1.28\tan\beta$ GeV (95%CL) in Type II two-doublet models.

[64] ABAZOV 02B search for a charged Higgs boson in top decays with $H^+ \to \tau^+ \nu$ at E_{cm}=1.8 TeV. For m_{H^+}=75 GeV, the region $\tan\beta > 32.0$ is excluded at 95%CL. The excluded mass region extends to over 140 GeV for $\tan\beta$ values above 100.

[65] BORZUMATI 02 point out that the decay modes such as $b\overline{b}W$, $A^0 W$, and supersymmetric ones can have substantial branching fractions in the mass range explored at LEP II and Tevatron.

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

[67] 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).

[68] 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.

[69] 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.

[70] 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.

[71] 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 $m_{H^+} > 0.97$ tanβ GeV (95%CL) is obtained for two-doublet models in which only one doublet couples to leptons.

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

[73] AMMAR 97B measure the Michel parameter ρ from $\tau \to e\nu\nu$ decays and assumes 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 $m_{H^+} > 0.97$ tanβ GeV (90% CL).

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

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

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

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

[78] ALAM 95 measure the inclusive $b \to s\gamma$ branching ratio at $\Upsilon(4S)$ and give B($b \to s\gamma$)$< 4.2 \times 10^{-4}$ (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.

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

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

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>97.3	95	[80] ABDALLAH	03	DLPH	$E_{cm} \leq 209$ GeV
>98.5	95	[81] ABBIENDI	02C	OPAL	$E_{cm} \leq 209$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[82] ABBIENDI	03Q	OPAL	$E_{cm} \leq 209$ GeV, single $H^{\pm\pm}$
		[83] GORDEEV	97	SPEC	muonium conversion
		[84] ASAKA	95	THEO	
>45.6	95	[85] ACTON	92M	OPAL	
>30.4	95	[86] ACTON	92M	OPAL	$T_3(H^{++})= +1$
>25.5	95	[86] ACTON	92M	OPAL	$T_3(H^{++})= 0$
none 6.5–36.6	95	[87] SWARTZ	90	MRK2	$T_3(H^{++}) = +1$
none 7.3–34.3	95	[87] SWARTZ	90	MRK2	$T_3(H^{++}) = 0$

[80] ABDALLAH 03 search for $H^{++}H^{--}$ pair production either followed by $H^{++} \to \tau^+\tau^+$, or decaying outside the detector. The limit is for weak single H^{++}. The limit for weak triplet is 98.1 GeV.

[81] ABBIENDI 02C searches for pair production of $H^{++}H^{--}$, with $H^{\pm\pm} \to \ell^\pm\ell^\pm$ (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 $g(H\ell\ell) \gtrsim 10^{-7}$.

[82] ABBIENDI 03Q searches for single $H^{\pm\pm}$ via direct production in $e^+e^- \to e^\pm e^\pm H^{\mp\mp}$, and via t-channel exchange in $e^+e^- \to e^+e^-$. In the direct case, and assuming B($H^{\pm\pm} \to \ell^\pm \ell^\pm$) = 1, a 95% CL limit on $h_{ee} < 0.071$ is set for $m_{H^{\pm\pm}} < 160$ GeV (see Fig. 6). In the second case, indirect limits on h_{ee} are set for $m_{H^{\pm\pm}} < 2$ TeV (see Fig. 8).

[83] 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 couplings 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.

[84] 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.

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

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

[87] SWARTZ 90 assume $H^{\pm\pm} \to \ell^\pm \ell^\pm$ (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.

H^0 and $H^\pm$ REFERENCES

ABDALLAH	04	EPJ C32 145	J. Abdallah *et al.*	(DELPHI Collab.)
ABBIENDI	03	PL B551 35	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	03B	EPJ C26 479	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	03F	EPJ C27 311	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	03G	EPJ C27 483	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	03Q	PL B577 93	G. Abbiendi *et al.*	(OPAL Collab.)
ABDALLAH	03	PL B552 127	J. Abdallah *et al.*	(DELPHI Collab.)
ACHARD	03C	PL B568 191	P. Achard *et al.*	(L3 Collab.)
HEISTER	03D	PL B565 61	A. Heister *et al.*	(ALEPH, DELPHI, L3+)
		ALEPH, DELPHI, L3, OPAL, LEP Higgs Working Group		
ABAZOV	02B	PRL 88 151803	V.M. Abazov *et al.*	(D0 Collab.)
ABBIENDI	02C	PL B526 221	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	02D	EPJ C23 397	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	02F	PL B544 44	G. Abbiendi *et al.*	(OPAL Collab.)
ABDALLAH	02	PL B525 17	J. Abdallah *et al.*	(DELPHI Collab.)
ACHARD	02C	PL B534 28	P. Achard *et al.*	(L3 Collab.)
ACHARD	02H	PL B545 30	P. Achard *et al.*	(L3 Collab.)
AKEROYD	02	PR D66 037702	A.G. Akeroyd *et al.*	
BORZUMATI	02	PL B549 170	F.M. Borzumati, A. Djouadi	
CHANOWITZ	02	PR D66 073002	M.S. Chanowitz	
HEISTER	02	PL B526 191	A. Heister *et al.*	(ALEPH Collab.)
HEISTER	02L	PL B544 16	A. Heister *et al.*	(ALEPH Collab.)
HEISTER	02M	PL B544 25	A. Heister *et al.*	(ALEPH Collab.)
HEISTER	02P	PL B543 1	A. Heister *et al.*	(ALEPH Collab.)
LEP	02	CERN-EP/2002-091	LEP Collabs.	
		ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group, and the SLD Heavy Flavor Group		
ABAZOV	01E	PRL 87 231801	V.M. Abazov *et al.*	(D0 Collab.)
ABBIENDI	01A	EPJ C19 587	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	01E	EPJ C18 425	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	01Q	PL B520 1	G. Abbiendi *et al.*	(OPAL Collab.)
ABREU	01F	PL B507 89	P. Abreu *et al.*	(DELPHI Collab.)
ACHARD	01C	PL B517 319	P. Achard *et al.*	(L3 Collab.)
AFFOLDER	01D	PRL 86 4472	T. Affolder *et al.*	(CDF Collab.)
AFFOLDER	01H	PR D64 092002	T. Affolder *et al.*	(CDF Collab.)
BARATE	01C	PL B499 53	R. Barate *et al.*	(ALEPH Collab.)
BARATE	01E	EPJ C19 213	R. Barate *et al.*	(ALEPH Collab.)
GAMBINO	01	NP B611 338	P. Gambino, M. Misiak	
ABBIENDI	00F	EPJ C12 567	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	00G	EPJ C14 51	G. Abbiendi *et al.*	(OPAL Collab.)
ACCIARRI	00M	PL B485 85	M. Acciarri *et al.*	(L3 Collab.)

ACCIARRI	00R	PL B489 102	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	00S	PL B489 115	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	00W	PL B496 34	M. Acciarri *et al.*	(L3 Collab.)
AFFOLDER	00I	PR D62 012004	T. Affolder *et al.*	(CDF Collab.)
BARATE	00L	PL B487 241	R. Barate *et al.*	(ALEPH Collab.)
FIELD	00	PR D61 013010	J.H. Field	
LEP	00B	CERN-EP-2000-055	LEP Collabs.	
PDG	00	EPJ C15 1	D.E. Groom *et al.*	
ABBIENDI	99E	EPJ C7 407	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	99O	PL B464 311	G. Abbiendi *et al.*	(OPAL Collab.)
ABBOTT	99B	PRL 82 2244	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	99E	PRL 82 4975	B. Abbott *et al.*	(D0 Collab.)
ABREU	99E	PL B446 75	P. Abreu *et al.*	(DELPHI Collab.)
Also	99N	PL B451 447 (erratum)	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	99P	PL B458 431	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	99Q	PL B459 367	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	99R	PL B460 484	P. Abreu *et al.*	(DELPHI Collab.)
ACKERSTAFF	99D	EPJ C8 3	K. Ackerstaff *et al.*	(OPAL Collab.)
CARENA	99B	hep-ph/9912223	M. Carena *et al.*	
CERN-TH/99-374				
CHANOWITZ	99	PR D59 073005	M.S. Chanowitz	
D'AGOSTINI	99	EPJ C10 663	G. D'Agostini, G. Degrassi	
FIELD	99	MPL A14 1815	J.H. Field	
LEP	99	CERN-EP/99-015	LEP Collabs. (ALEPH, DELPHI, L3, OPAL, LEP EWWG+)	
ABBOTT	98	PRL 80 442	B. Abbott *et al.*	(D0 Collab.)
ABE	98T	PRL 81 5748	F. Abe *et al.*	(CDF Collab.)
ACKERSTAFF	98S	EPJ C5 19	K. Ackerstaff *et al.*	(OPAL Collab.)
ACKERSTAFF	98Y	PL B437 218	K. Ackerstaff *et al.*	(OPAL Collab.)
CHANOWITZ	98	PRL 80 2521	M. Chanowitz	
DAVIER	98	PL B435 427	M. Davier, A. Hoecker	
GONZALEZ-G...	98B	PR D57 7045	M.C. Gonzalez-Garcia, S.M. Lietti, S.F. Novaes	
HAGIWARA	98B	EPJ C2 95	K. Hagiwara, D. Haidt, S. Matsumoto	
PDG	98	EPJ C3 1	C. Caso *et al.*	
ABBANEO	97	CERN-PPE/97-154	D. Abbaneo *et al.*	
ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, and the LEP Electroweak Working Group.				
ABE	97L	PRL 79 357	F. Abe *et al.*	(CDF Collab.)
ABE	97W	PRL 79 3819	F. Abe *et al.*	(CDF Collab.)
ACCIARRI	97F	PL B396 327	M. Acciarri *et al.*	(L3 Collab.)
AMMAR	97B	PRL 78 4686	R. Ammar *et al.*	(CLEO Collab.)
COARASA	97	PL B406 337	J.A. Coarasa, R.A. Jimenez, J. Sola	
DEBOER	97B	ZPHY C75 627	W. de Boer *et al.*	
DEGRASSI	97	PL B394 188	G. Degrassi, P. Gambino, A. Sirlin	(MPIM, NYU)
DITTMAIER	97	PL B391 420	S. Dittmaier, D. Schildknecht	(BIEL)
GORDEEV	97	PAN 60 1164	V.A. Gordeev *et al.*	(PNPI)
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GUCHAIT	97	PR D55 7263	M. Guchait, D.P. Roy	(TATA)
KRAWCZYK	97	PR D55 6968	M. Krawczyk, J. Zochowski	(WARS)
MANGANO	97	PL B410 299	M. Mangano, S. Slabospitsky	
RENTON	97	IJMP A12 4109	P.B. Renton	
STAHL	97	ZPHY C74 73	A. Stahl, H. Voss	(BONN)
ALCARAZ	96	CERN-PPE/96-183	J. Alcaraz *et al.*	
The ALEPH, DELPHI, L3, OPAL, and SLD Collaborations and the LEP Electroweak Working Group				
ALEXANDER	96H	ZPHY C71 1	G. Alexander *et al.*	(OPAL Collab.)
ELLIS	96C	PL B389 321	J. Ellis, G.L. Fogli, E. Lisi	(CERN, BARI)
GURTU	96	PL B385 415	A. Gurtu	(TATA)
PDG	96	PR D54 1	R. M. Barnett *et al.*	
ABREU	95H	ZPHY C67 69	P. Abreu *et al.*	(DELPHI Collab.)
ALAM	95	PRL 74 2885	M.S. Alam *et al.*	(CLEO Collab.)
ASAKA	95	PL B345 36	T. Asaka, K.I. Hikasa	(TOHOK)
BUSKULIC	95	PL B343 444	D. Buskulic *et al.*	(ALEPH Collab.)
GROSSMAN	95B	PL B357 630	Y. Grossman, H. Haber, Y. Nir	
GROSSMAN	94	PL B332 373	Y. Grossman, Z. Ligeti	
STAHL	94	PL B324 121	A. Stahl	(BONN)
ACTON	92M	PL B295 347	P.D. Acton *et al.*	(OPAL Collab.)
PICH	92	NP B388 31	A. Pich, J. Prades, P. Yepes	(CERN, CPPM)
SWARTZ	90	PRL 64 2877	M.L. Swartz *et al.*	(Mark II Collab.)