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 the simplest form of this mechanism, which is implemented in the SM, fundamental scalar "Higgs" fields fill the vacuum and 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 $\mathrm{U(1)}_{\mathrm{EM}}$ 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 [4] 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 a possible 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 [5,6]) 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 smaller than about 135 GeV.

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). In the LEP1 phase, the collider was operating at center-of-mass energies close to M_Z. During the LEP2 phase, the energy was increased in steps, 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 bosons with masses up to about 117 GeV and to charged Higgs bosons with masses up to about 80 GeV.

Higgs boson searches have also been carried out at the Tevatron $p\overline{p}$ collider. With the presently available data samples, the sensitivity of the two experiments, CDF and DØ, is still rather limited, but with increasing 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 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/pdg2006/index.html`.

II. The Standard Model Higgs boson

The mass of the SM Higgs boson H^0 is given by $m_H = \sqrt{2\lambda} \cdot\ v$. While the vacuum expectation value of the Higgs field, $v = (\sqrt{2} \cdot G_F)^{-1/2} = 247$ GeV, is fixed by the Fermi coupling G_F, the quartic Higgs self-coupling λ is a free parameter; thus, the mass m_{H^0} is not predicted by the SM. However, arguments based on the perturbativity of the theory can be used to place approximate upper and lower bounds upon the mass [13]. Since for large Higgs boson masses the 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 from requiring the effective potential to be positive definite. These theoretical bounds imply that if the SM is to be perturbative 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 $m_{H^0} = 91^{+45}_{-32}$ GeV, or $m_{H^0} <$186 GeV at the 95% confidence level (CL) [14], which is consistent with the SM being valid up to the GUT scale. (These values are obtained using a top quark mass of 172.7 ± 2.9 GeV [15] in the fit.)

The principal mechanism for producing the SM Higgs particle in e^+e^- collisions at LEP energies is Higgs-strahlung in the s-channel [16], $e^+e^- \rightarrow H^0Z^0$. The Z^0 boson in the final state is either virtual (LEP1), or on mass shell (LEP2). 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. The production cross sections are given in Ref. 18.

The most relevant decays of the SM Higgs boson [18,19] are summarised in Fig. 1. For masses below about 130 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 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 $mh^0 = 500$ GeV.

At hadron colliders, the most important Higgs production processes are [20]: gluon fusion ($gg \to H^0$), Higgs production in association with a vector boson ($W^\pm H^0$ or Z^0H^0) or with a top quark pair ($t\overline{t}H^0$), and the W^+W^- fusion process (qqH^0 or $q\overline{q}H^0$). At the Tevatron and for masses less than about 130 GeV (where the Higgs boson mainly decays to $b\overline{b}$), the most promising discovery channels are $W^\pm H^0$ and Z^0H^0 with $H^0 \to b\overline{b}$. The contribution of $H^0 \to W^*W$ is important towards higher masses. At the future pp collider LHC, the gluon fusion channels $gg \to H^0 \to \gamma\gamma$, W^+W^-, Z^0Z^0, the associated production channel $t\overline{t}H^0 \to t\overline{t}b\overline{b}$ and the W^+W^- fusion channel $qqH^0 \to qq\tau^+\tau^-$ are all expected to contribute.

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

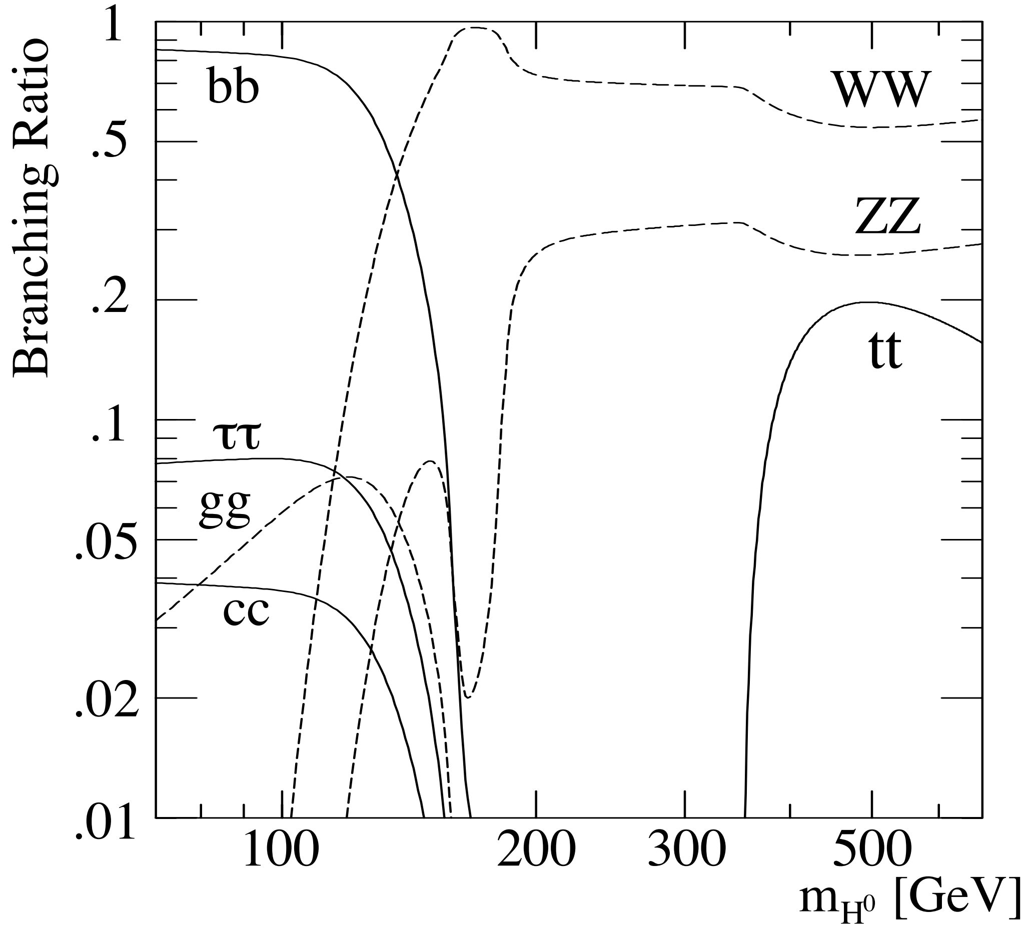

Figure 1: Branching ratios for the main decays of the SM Higgs boson (from Ref. 10).

Higgs boson [21]. Substantial data samples have also been collected during the LEP2 phase at energies up to 209 GeV.

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

- The four-jet topology $e^+e^- \to (H^0 \to b\bar{b})\ (Z^0 \to q\overline{q})$ is the most abundant process; it 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.

- 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.
- 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.
- Final states with tau leptons are produced in the processes $e^+e^- \rightarrow (H^0 \rightarrow \tau^+\tau^-)(Z^0 \rightarrow q\overline{q})$ and $(H^0 \rightarrow q\overline{q})(Z^0 \rightarrow \tau^+\tau^-)$; 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 all four search topologies have been 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 a preselection, which reduces the main background processes (from two-photon exchange, $e^+e^- \rightarrow$ fermion pairs, W^+W^- and Z^0Z^0), 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 $s + b$ case, it is assumed that a SM Higgs boson of hypothetical mass, m_H is produced, in addition to the SM background processes (the

b case). 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 $1 - CL_b = 1 - \mathcal{P}_b(Q \leq Q_{\text{observed}})$ and $CL_{s+b} = \mathcal{P}_{s+b}(Q \leq Q_{\text{observed}})$, which measure the compatibility of the observed data configuration with the two hypotheses [22].

The searches carried out at LEP prior to the year 2000 did not reveal any evidence for the production of a SM Higgs boson. However, in the data of the year 2000, mostly at energies higher than 205 GeV, ALEPH reported an excess of about three standard deviations [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] did show evidence for such an excess, but could not, however, exclude a 115 GeV Higgs boson. When the data of the four experiments are combined [27], the overall significance of a possible signal is 1.7 standard deviations. Fig. 2 shows the test statistic $-2\ln Q$ for the ALEPH data and for the LEP data combined. For a hypothetical 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. The same combination of LEP data provides a 95% CL lower bound of 114.4 GeV is obtained for the mass of the SM Higgs boson.

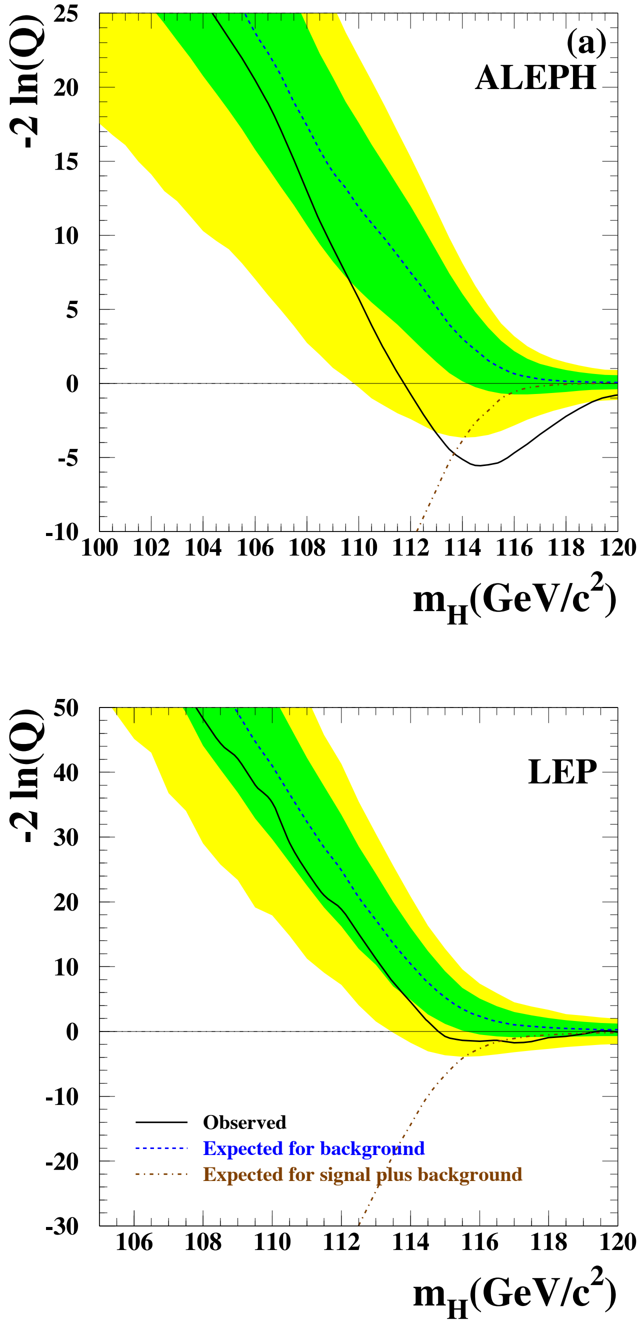

Figure 2: Observed (solid line), and expected behaviors of the test statistic $-2\ln Q$ for the background (dashed line), and the signal + background hypothesis (dash-dotted line) as a function of the test mass m_H. Left: ALEPH data alone; right: LEP data combined. The dark and light shaded areas represent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

At the Tevatron, the searches concentrate on the associated production, $p\overline{p} \to VH^0$, with a vector boson $V(\equiv Z^0, W^{\pm})$ decaying into charged leptons and/or neutrinos [28]. At masses below about 130 GeV the $H^0 \to b\overline{b}$ decay provides the most sensitive search channels while at higher masses the search for $H^0 \to W^+W^-$ (one of the $W^{\pm}$ bosons may be virtual) becomes relevant. The currently available data samples allow model-independent upper bounds to be set on the cross section for Higgs-like event topologies [29]. These bounds are still far from testing the SM predictions (see Fig. 3), but the sensitivity of the searches is continuously improving with more statistics.

III. Higgs bosons in the MSSM

Most of the experimental investigations carried out in the past at LEP and at the Tevatron assume CP conservation (CPC) in the MSSM Higgs sector. This assumption implies that the three netural Higgs bosons are CP eigenstates. However, CP-violating (CPV) phases in the soft SUSY breaking sector can lead through quantum effects to sizeable CP violation in the MSSM Higgs sector [31,32]. Such scenarios are theoretically appealing, since they provide one of the ingredients for explaining the observed cosmic matter-antimatter asymmetry [33,34]. In such models, the three neutral Higgs mass eigenstates are mixtures of CP-even and CP-odd fields. Their production and decay properties may differ considerably from the predictions of the CPC scenario [32]. The CPV scenario has recently been investigated at LEP [35,36].

An important prediction of the MSSM, both CPC and CPV, is the relatively small mass of the lightest neutral scalar boson, less than about 135 GeV after radiative corrections [37,38], which emphasizes the importance of the searches at currently available and future accelerators.

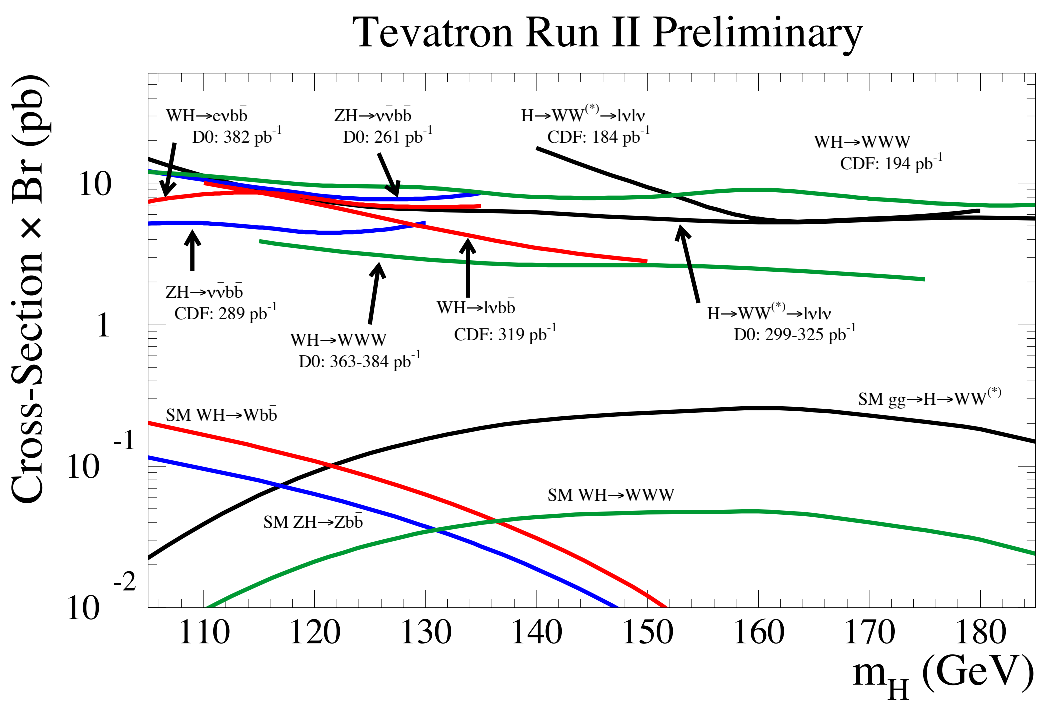

Figure 3: Upper bounds, obtained by the Tevatron experiments CDF and D0, for the cross-sections of event topologies motivated by Higgs boson production in the SM. The curves in the opper part represent the 95% CL experimental limits; the curves in the lower part are the SM predictions (from Ref. 30). See full-color version on color pages at end of book.

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.

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 [37,38], especially in the neutral Higgs sector. The largest contributions arise from the incomplete cancellation between top and scalar-top (stop) loops which depend strongly on the top quark mass ($\sim m_{\mathrm{t}}^4$) and logarithmically on the stop masses. Furthermore, the corrections affecting the masses and production- and decay-properties depend on the details of soft SUSY breaking, and on the mixing between the SUSY partners of left- and right-handed top and bottom quarks (stop and sbottom mixing).

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

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

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

with the kinematic factor

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

and $\lambda_{ij} = [1 - (m_i + m_j)^2/s][1 - (m_i - m_j)^2/s]$, where the s is the square of the e^+e^- collision energy. These Higgs-strahlung and pair production cross sections are complementary since $\sin^2(\beta - \alpha) + \cos^2(\beta - \alpha) = 1$. Typically, the process $e^+e^- \to h^0 Z^0$ is more abundant at small $\tan\beta$ and $e^+e^- \to h^0 A^0$ at large $\tan\beta$ or at $m_{A^0} \gg M_Z$; but the latter can also be suppressed by the kinematic factor $\overline{\lambda}$. The cross sections for the heavy scalar boson H^0 are obtained by interchanging $\sin^2(\beta - \alpha)$ and $\cos^2(\beta - \alpha)$ in Eqs. 1 and 2, and replacing the index h^0 by H^0 in Eqs. 1, 2, and 3.

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. At the Tevatron, the associated production $p\overline{p} \to (h^0$ or $H^0)V$ (with $V \equiv W^\pm$, Z^0), and the Yukawa process $p\overline{p} \to h^0 b\overline{b}$ 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.

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.

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

The following decay features are relevant to the MSSM. The h^0 boson will decay mainly to fermion pairs, since the mass, less than about 135 GeV, is below the W^+W^- threshold. 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 8%. Decays to $c\overline{c}$ and gluon pairs may become important for $\tan\beta < 1$ or for particular parameter choices where the decays to $b\overline{b}$ and $\tau^+\tau^-$ are suppressed. The decay $h^0 \to A^0A^0$ may be dominant where 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 exploit the complementarity of the Higgs-strahlung process $e^+e^- \to h^0Z^0$ and the pair production process $e^+e^- \to h^0A^0$, expressed by Eqs. 1 and 2. For Higgs-strahlung, the searches for the SM Higgs boson are reinterpreted, taking into account the MSSM reduction factor $\sin^2(\beta-\alpha)$; for pair production, searches are performed specifically for the $(b\overline{b})(b\overline{b})$ and $(\tau^+\tau^-)(q\overline{q})$ final states.

The search results are interpreted in a constrained MSSM where universal values are assumed for the soft SUSY breaking parameters: the sfermion and gaugino masses $M_{\rm SUSY}$ and M_2, the Higgs mixing parameter μ and the universal trilinear Higgs-fermion coupling $A = A_{\rm t} = A_{\rm b}$ to up and down quarks. Besides these parameters, the gluino mass and the precise value of the top quark mass also affect the Higgs boson masses and couplings. The interpretations are limited to a number of specific "benchmark" models [38] where all these parameters take fixed values. Some of these models are chosen to illustrate parameter choices where the detection of Higgs bosons at LEP or in *pp*-collisons is expected to be difficult *a priori* due to the suppression of some main discovery channels. Of particular interest is the $m_{h^0}-max$ scenario which is designed to maximize the allowed values of m_{h^0} for a given $\tan\beta$ and fixed values of $M_{\rm SUSY}$ and m_t, and therefore yields conservative exclusion limits.

The limits from the four LEP experiments are described in Refs. [23,24,35,39] and the combined LEP limits presented in [36] There is no excess in the combined data which could be interpreted as a compelling evidence for Higgs boson production. However, several local fluctuations, with significances between two and three standard deviations, are observed. A number of such excesses are indeed expected from statistical fluctuations of the background, due to the large number of individual searches which were conducted to cover the whole parameter space. The combined LEP limits are shown in Fig. 4 for the m_{h^0}-max scenario, in the (m_{h^0}, tan β) parameter projection (see Ref. 36 for other projections and other benchmark models). In this scenario, The 95% CL mass bounds are m_{h^0} >92.8 GeV, m_{A^0} >93.4 GeV; furthermore, values of $\tan\beta$ from 0.7 to 2.0

are excluded. One should note that the exclusion in $\tan\beta$ can be smaller if the top mass turns out to be higher than the assumed value of 174.3 GeV, or if M_{SUSY} is taken to be larger than the assumed value of 1 TeV. Furthermore, the uncertainty on m_{h^0} from higher-order corrections which are not included in the current calculations is about 3 GeV.

The neutral Higgs bosons may also be produced by Yukawa processes $e^+e^- \to f\overline{f}\phi$, where the Higgs particle $\phi \equiv h^0$, H^0, A^0, is radiated off a massive fermion ($f \equiv$ b or $\tau^{\pm}$). These processes can be dominant at low masses, and whenever the $e^+e^- \to h^0Z^0$ and h^0A^0, processes 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 used to search for $b\overline{b}b\overline{b}$, $b\overline{b}\tau^+\tau^-$, and $\tau^+\tau^-\tau^+\tau^-$ final states [40,41]. Regions of low mass and high enhancement factors are excluded by these searches.

In $p\overline{p}$ collisions at Tevatron energies, the searches are testing primarily the region of $\tan\beta$ larger than about 50, where the cross sections for the production of neutral Higgs bosons are enhanced. Hence, they efficiently complement the LEP searches. The D0 and CDF experiments have published on searches for neutral Higgs bosons produced in association with bottom quarks and decaying into $b\overline{b}$ [42,43]. CDF also addresses inclusive production with subsequent Higgs boson decays to $\tau^+\tau^-$ [44]. The currently excluded domains are shown in Fig. 5, together with the LEP limits, in the $(m_{A^0}, \tan\beta)$ projection. The sensitivity is expected to improve with the continuously growing data samples; eventually $\tan\beta$ down to about 20 will be tested.

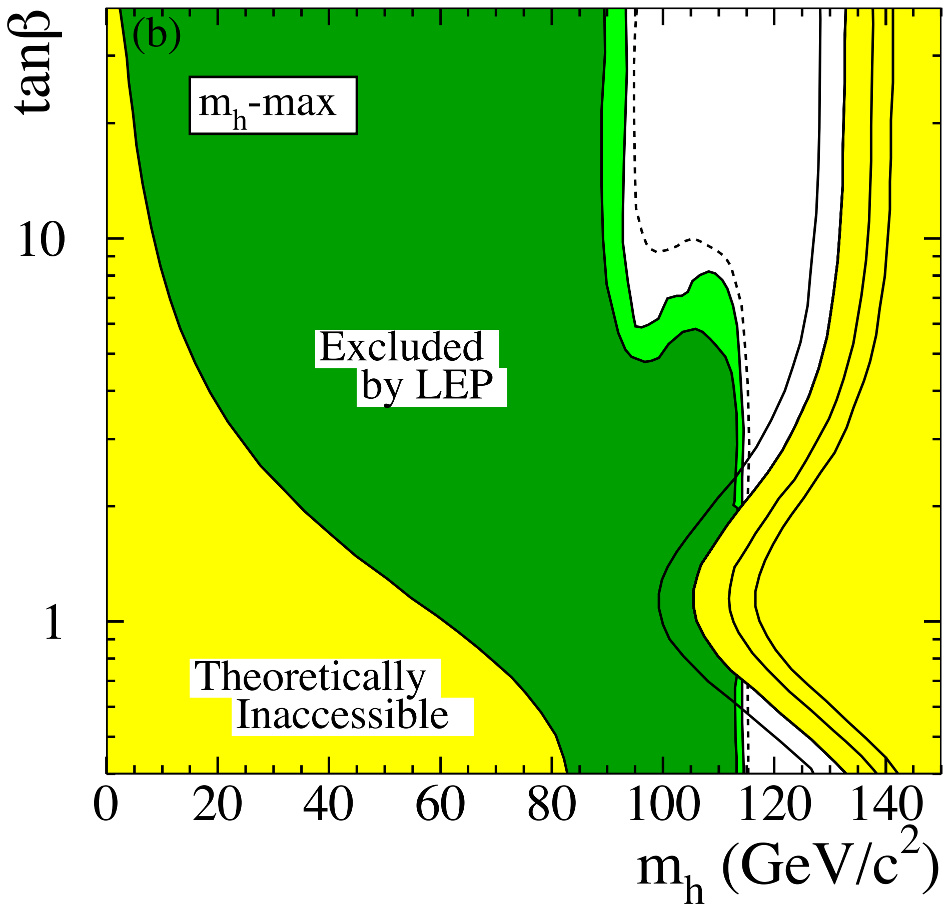

Figure 4: The MSSM exclusion limits, at 95% CL (light-green) and 99.7% CL (dark-green), obtained by LEP for the m_{h_0}-*max* benchmark scenario, with $m_{\rm t}$ = 174.3 GeV. The figure shows the excluded and theoretically inaccessible regions in the $(m_{h_0}, \tan\beta)$ projection. The upper edge of the parameter space is sensitive to the top quark mass; it is indicated, from left to right, for $m_{\rm t}$ = 169.3, 174.3, 179.3 and 183.0 GeV. The dashed lines indicate the boundaries of the regions which are expected to be excluded on the basis of Monte Carlo simulations with no signal (from Ref. 36). See full-color version on color pages at end of book.

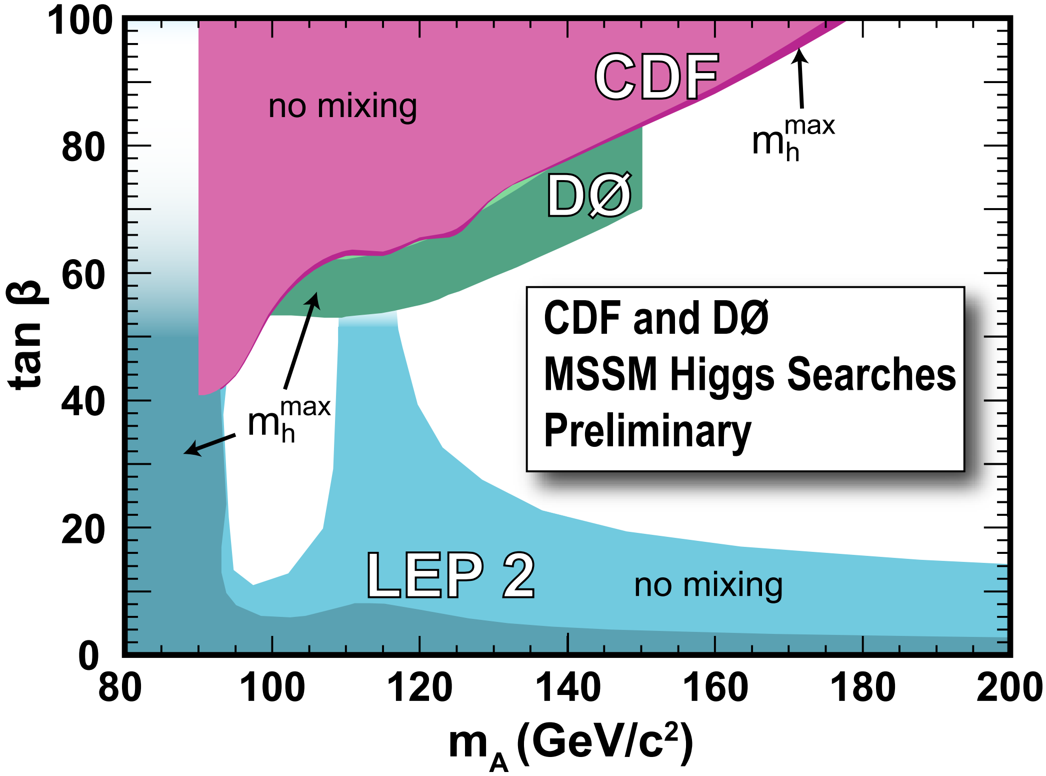

Figure 5: The MSSM exclusion limits, at 95% CL obtained by the Tevatron experiments CDF and D0, and by LEP, for the *no-mixing* (light color shadings) and the $m_{H^0} - max$ (darker color shadings) benchmark scenarios, projected onto the $(m_{A^0}, \tan\beta)$ plane of the parameter space. CDF uses a data sample of 310 pb^{-1} to search for the $\tau^+\tau^-$ final state, and D0 uses 260 pb^{-1} of data to search for the $h^0 \to b\bar{b}$ final state. One should be aware that the exclusion is sensitive to the sign and magnitude of the Higgs mass parameter used, namely $\mu = -200$ GeV. The LEP limits are obtained for a top quark mass of 174.3 GeV (the Tevatron results are not sensitive to the precise value of the top mass). See full-color version on color pages at end of book.

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 CP-invariant at tree level, substantial CP asymmetry can be generated by radiative contributions, *e.g.*, from third generation scalar-quarks [31,32].

In the CPV MSSM scenario, the three neutral Higgs eigenstates $H_i \quad (i = 1, 2, 3)$ 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, $e^+e^- \to H_i H_j \quad (i \neq j)$, with rates which depend on the details of CP violation. 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. Altogether, the searches in the CPV MSSM scenario are experimentally more challenging and hence, a lesser exclusion power is anticipated than in the CPC MSSM scenario.

The cross section for the Higgs-strahlung and pair production processes are given by [32]

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

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

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

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

$$g_{H_i H_j Z} = \mathcal{O}_{3i}(\cos\beta \mathcal{O}_{2j} - \sin\beta \mathcal{O}_{1j}) - \mathcal{O}_{3j}(\cos\beta \mathcal{O}_{2i} - \sin\beta \mathcal{O}_{1i}) \tag{7}$$

obey the relations

$$\sum_{i=1}^{3} g^2_{\mathrm{H}_i\mathrm{ZZ}} = 1 \tag{8}$$

$$g_{\mathrm{H}_k\mathrm{ZZ}} = \varepsilon_{ijk} g_{\mathrm{H}_i\mathrm{H}_j\mathrm{Z}} \tag{9}$$

where ε_{ijk} is the usual Levi-Civita symbol.

The orthogonal matrix $\mathcal{O}_{ij}$ $(i,j = 1,2,3)$ relating the weak CP eigenstates to the mass eigenstates has all off-diagonal entries different from zero in the CP-violating scenario. The elements giving rise to CP-even/odd mixing are proportional to

$$\frac{m_t^4}{v^2}\frac{\mathrm{Im}(\mu\mathrm{A})}{\mathrm{M}^2_{\mathrm{SUSY}}}, \tag{10}$$

with $v = \sqrt{v_1^2 + v_2^2}$ (the other parameters are defined in Section 3.1). Their size is a measure of the effects from CP violation in the Higgs sector.

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 $\tau^+\tau^-$. If kinematically allowed, the other two neutral Higgs bosons H_2 and H_3 will decay predominantly to H_1H_1; otherwise they decay preferentially to $b\overline{b}$.

The LEP searches [35,36] are performed for a "benchmark scenario" [45], where the parameters are chosen in such a way as to maximize the expression in Eq. 10 and hence the phenomenological differences with respect to the CPC scenario. In the choice of the parameter values, constraints from measurements of the electron electric dipole moment had to be taken into account [46]. Fig. 6 shows the exclusion limits of LEP in the $(m_{\mathrm{H}_1}, \tan\beta)$ plane. As anticipated, one observes a reduction of the exclusion power as compared to the CPC scenario, especially in the region of $\tan\beta$ between 4 and 10. Values of $\tan\beta$ less than about 3 are excluded in this scenario; however, no absolute lower bound can be set for the mass of the lightest neutral Higgs boson H_1. Similar exclusion plots, for other choices of model parameters, can be found in Ref. 36.

IV. Charged Higgs bosons

Charged Higgs bosons are predicted by models with two Higgs field doublets (2HDM), thus also in the MSSM [6]. 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.

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 [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 branching ratios are model-dependent. In 2HDM of "type 2," [1]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 from them. 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 search results are usually presented as a function of the $H^+ \to \tau^+\nu$ branching ratio.

The searches of the four LEP experiments are described in Ref. [47]. Their sensitivity is limited to $m_{H^\pm}$ less than

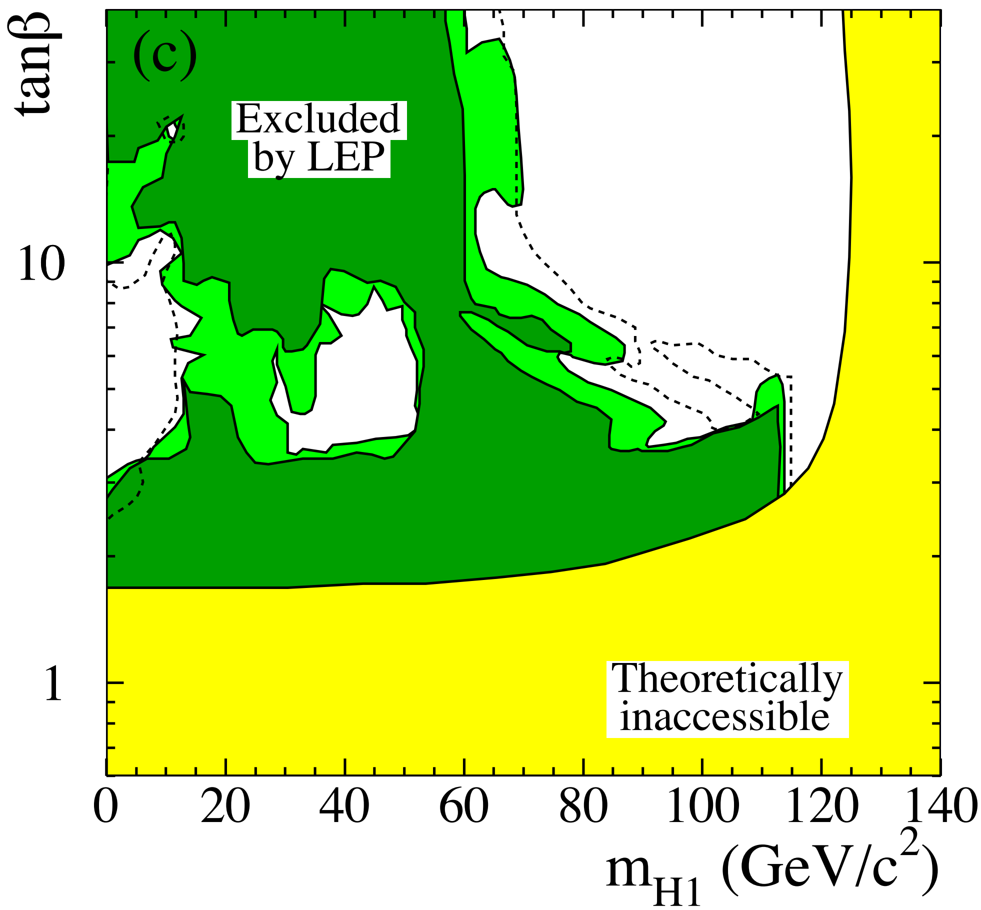

Figure 6: The MSSM exclusion limits, at 95% CL (light-green) and 99.7% CL (dark-green), obtained by LEP for a CP-violating scenario with $\mu = 2$ TeV and $M_{SUSY} = 500$ GeV, and with $m_{\rm t} = 174.3$ GeV. The figure shows the excluded and theoretically inaccessible regions in the $(m_{\rm H_1}, \tan\beta)$ projection. The dashed lines indicate the boundaries of the regions which are expected to be excluded on the basis of Monte Carlo simulations with no signal (from Ref. 36). See full-color version on color pages at end of book.

about M_W due to the background from $e^+e^- \to W^+W^-$.

The combined LEP data [48] exclude a charged Higgs boson with mass less than 78.6 GeV (95% CL) (valid for arbitrary $H^+ \to \tau^+\nu$ branching ratio). The region excluded in the ($\tan\beta$ $m_{H^\pm}$) plane is shown in Fig. 7. These exclusions are valid for the 2HDM of "type 2."

In the 2HDM of "type 1" [49], 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 dominant for masses accessible at LEP. This eventuality is investigated by DELPHI [50].

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 $t \to bW^+$. In the 2HDM of "type 2," the decay $t \to bH^+$ could have a detectable rate for $\tan\beta$ less than one, or larger than about 30.

Earlier searches of the D0 and CDF collaborations are summarised in Ref. [51]. A more recent search of CDF is presented in [52]. It is based on $t\overline{t}$ cross section measurements in the di-lepton, lepton+jet and lepton+($\tau \to$ hadrons) event topologies. By comparing the results to the corresponding SM cross sections ($t \to bW^+$ only), the CDF search provides limits on the $t \to bH^+$ branching ratio, which are converted to exclusions in the ($\tan\beta$, $m_{H^\pm}$) plane. Such an exclusion is shown in Fig. 7, along with the LEP exclusion, for a choice of MSSM parameters which is almost identical to the $m_{h^0} - max$ benchmark scenario adopted by the LEP collaborations in their search for neutral MSSM Higgs bosons.

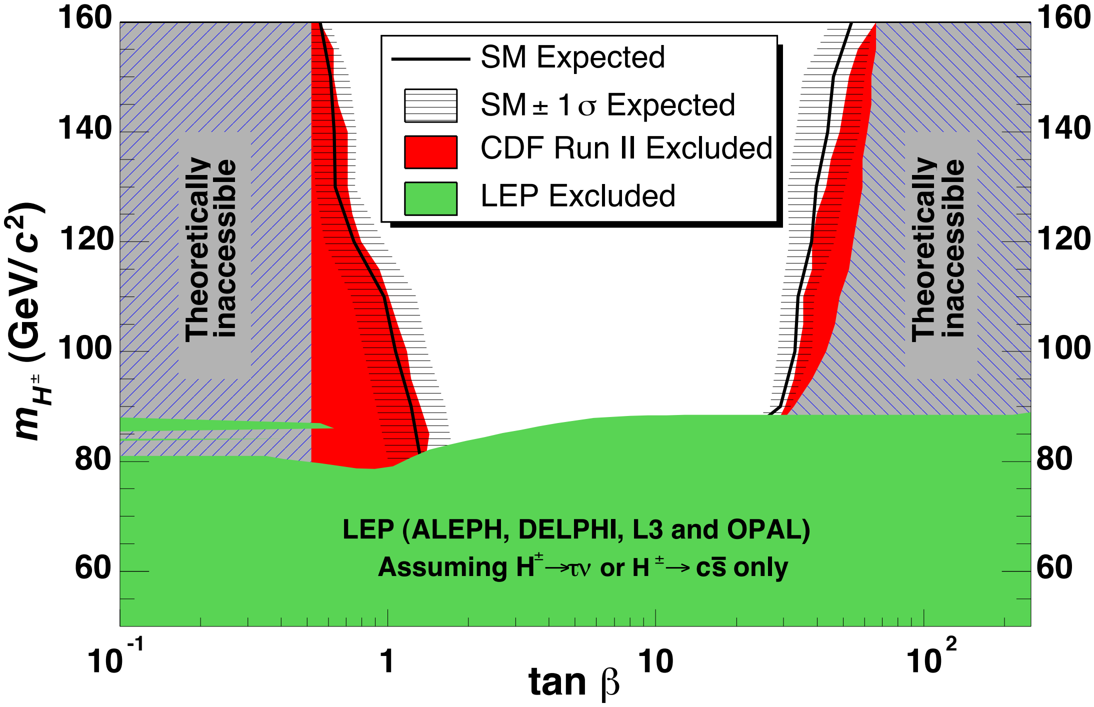

Figure 7: Summary of the 95% CL exclusions in the $(m_{H^+}, \tan\beta)$ plane obtained by LEP [48] and CDF. The size of the data sample used by CDF, the choice of the top quark mass, and the soft SUSY breaking parameters to which the CDF exclusions apply, are indicated in the figure. The full lines indicate the SM expectation (no $H^{\pm}$ signal) and the horizontal hatching represents the $\pm 1\sigma$ bands about the SM expectation (from Ref. 52). See full-color version on color pages at end of book.

Indirect limits in the $(m_{H^\pm}, \tan\beta)$ plane are obtained by comparing the measured rate of the flavor-changing neutral-current process $b \rightarrow s\gamma$ to the SM prediction. In the SM, this process is mediated by virtual $W^{\pm}$ exchange [53], while in the 2HDM of "type 2," the branching ratio is altered by contributions from the exchange of charged Higgs bosons [54]. The current experimental value, from combining ALEPH, CLEO, BELLE, and BABAR [55], is in agreement with the SM prediction and sets a lower bound of about 320 GeV (95% CL) for $m_{H^\pm}$. This exclusion 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, are predicted, for example, by models with additional triplet scalar fields or left-right symmetric models [56]. It has been emphasized that the see-saw mechanism could lead to doubly-charged Higgs bosons with masses which are accessible to current and future colliders [57]. Searches were performed at LEP for the pair-production process $Z^0 \to H^{++}H^{--}$ with four prompt leptons in the final state [58–60]. 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 [61]. Furthermore, such particles 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 [60,61].

Searches have also been carried out at the Tevatron for the pair production process $p\overline{p} \to H^{++}H^{--}$. While the D0 search is limited to the $\mu^+\mu^+\mu^-\mu^-$ final state [62], CDF also considers the $\mathrm{e}^+\mathrm{e}^+\mathrm{e}^-\mathrm{e}^-$ and $\mathrm{e}^+\mu^+\mathrm{e}^-\mu^-$ [63]. Lower bounds are obtained for left- and right-handed $H^{\pm\pm}$ bosons. For example, assuming 100% branching ratio for $H^{\pm\pm} \to \mu^\pm\mu^\pm$, the CDF data exclude a left- and a right-handed doubly charged Higgs boson with mass larger than 136 GeV and 113 GeV, respectively, at the 95% CL. A search of CDF for long-lived $H^{\pm\pm}$ boson, which would decay outside the detector, is described in [64].

The current status of coupling limits, from direct searches at LEP and at the Tevatron, is summarised in Fig. 8.

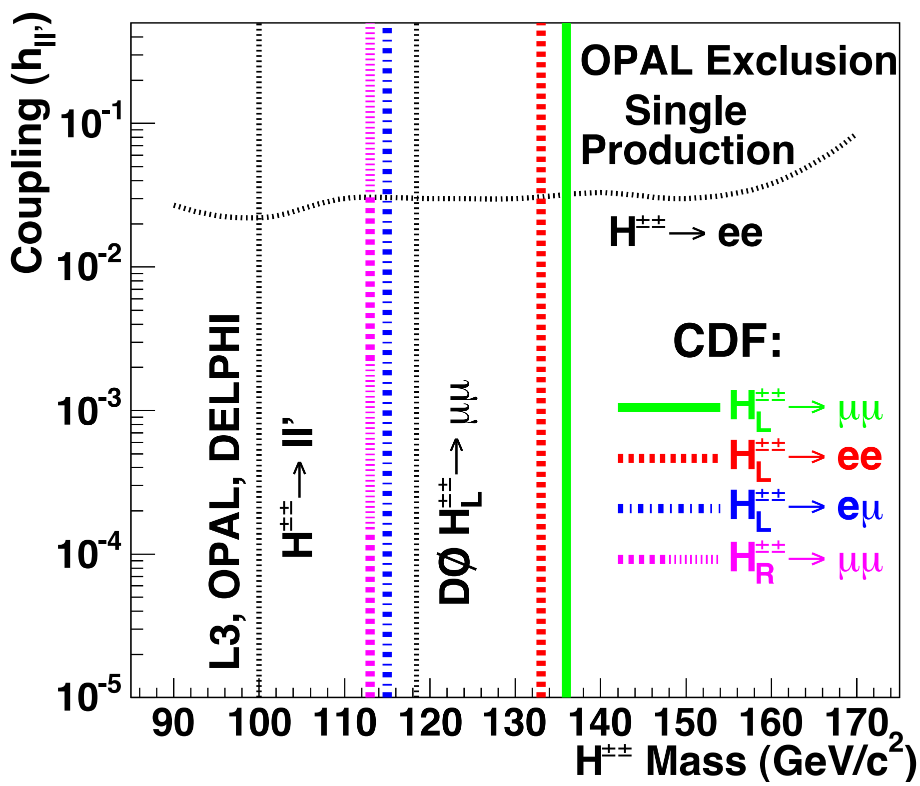

Figure 8: The 95% c.l. exclusion limits on the couplings to leptons of right- and left-handed doubly-charged Higgs bosons, obtained by LEP and Tevatron experiments (from Ref. 63). See full-color version on color pages at end of book.

V. Model extensions

The addition of a singlet scalar field to the CP-conserving MSSM [65] 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 140 GeV for the mass of the lightest neutral CP-even scalar. The DELPHI collaboration places a constraint on such models [66].

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 [67]. 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 by using the beam energy constraint. Results from the LEP experiments can be found in Refs. [23,68]. A preliminary combination of LEP data yields a 95% CL lower bound of 114.4 GeV for the mass of a Higgs boson, if it is produced with SM production rate, and if it decays exclusively into invisible final states [69].

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 assumption that the Higgs bosons have a sizeable $b\overline{b}$ decay branching ratio. However, in the general 2HDM case, decays to non-$b\overline{b}$ final states may be strongly enhanced. More recently some flavor-independent searches have been reported at LEP which do not require the experimental signature of b flavor [70]; also, a preliminary combination of LEP data has been performed [71]. In conjunction with the older, b-flavor sensitive searches, large domains of the general 2HDM parameter space of "type 2" have been excluded [72].

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 have a low rate due to $W^\pm$ and top quark loops [73]. Additional loops from SUSY particles would increase the rates only slightly [74], 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 limits on such anomalous couplings. Furthermore, they constrain the so-called "fermiophobic" 2HDM of "type 1" [75], which also predicts an enhanced $h^0 \to \gamma\gamma$ rate. The LEP searches are described in [76,77]. In a preliminary combination of LEP data [78], 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 [79]. 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 L3 [77].

The searches for netural Higgs bosons were used by DELPHI to place mass-dependent upper bounds on a number of Higgs-motivated event topologies [41], which apply to a large class of models. OPAL have performed a decay-mode independent search for the Bjorken process $e^+e^- \to\ S^0Z^0$ [80], 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); it produces upper bounds on the cross section for scalar masses between 10^{-6} GeV to 100 GeV.

VI. Prospects

The LEP collider stopped producing data in November 2000. At the Tevatron, performance studies suggest [8] that data samples in excess of 2 fb^{-1} per experiment would extend the combined sensitivity of CDF and D0 beyond the LEP reach. With 4 fb^{-1} per experiment, the Tevatron should be able to exclude, at 95% CL, a SM Higgs boson with mass up to about 130GeV; with 9 fb^{-1} per experiment, it could produce a 3σ evidence for a Higgs boson of 130 GeV mass. Data samples of this size 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 searches based on a large number 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 simultaneous discovery of several of the Higgs bosons is possible over extended domains of the parameter space.

A high-energy e^+e^- linear collider can be realized after the year 2010. It could be running initially at a center-of-mass energy 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 [81]. Furthermore, running in the photon collider mode, the linear collider could be used to produce Higgs bosons in the s-channel.

Higgs production in the s-channel would also be possible at a future $\mu^+\mu^-$ [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 symmetry breaking and the scale hierarchy problem without introducing supersymmetry. The "little Higgs model" [82] proposes an additional set of heavy vector-like quarks, gauge bosons, and scalar particles, in the 100 GeV-1 TeV mass scale. Their couplings are tuned in such a way that the quadratic divergences induced in the SM by the top, gauge-boson and Higgs loops are cancelled at one-loop level. If the Little Higgs mechanism is indeed a valid alternative to supersymmetry, it should be possible to detect some of these new states at the LHC.

Alternatively, models with extra space dimensions [83] propose a natural way for avoiding the scale hierarchy problem. In this class of models, the Planck scale may lose its fundamental character to become merely an effective scale in 3-dimensional space. These models predict a light Higgs-like particle, the radion, which differs from the Higgs boson, for example, in its enhanced coupling to gluons. A first search for the radion in LEP data, conducted by OPAL, gave negative results [84].

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 [85] expected in theories with dynamical symmetry breaking [86].

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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 compilation, 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	06	D0	$p\overline{p} \rightarrow H^0 X$, $H^0 \rightarrow W W^*$
		[5] ABAZOV	05F	D0	$p\overline{p} \rightarrow H^0 W X$
		[6] ACOSTA	05K	CDF	$p\overline{p} \rightarrow H^0 Z X$
		[7] ABAZOV	01E	D0	$p\overline{p} \rightarrow H^0 W X$, $H^0 Z X$
		[8] 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 06 search for Higgs boson production in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with the decay chain $H^0 \rightarrow W W^* \rightarrow \ell^+\nu\ell'\overline{\nu}$. A limit $\sigma(H^0)\cdot B(H0 \rightarrow W W^*) <$ (3.9–9.5) pb (95 %CL) is given for $m_{H^0} = 120$–200 GeV, which far exceeds the expected Standard Model cross section.

[5] ABAZOV 05F search for associated $H^0 W$ production in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV in the final state $W \rightarrow e\nu$, $H^0 \rightarrow b\overline{b}$. A limit $\sigma(W H^0)\cdot B(H^0 \rightarrow b\overline{b}) <$ [9.0, 9.1, 12.2] pb (95 %CL) is given for $m_{H^0} =$ [115, 125, 135] GeV, which far exceeds the expected Standard Model cross section.

[6] ACOSTA 05K search for associated $H^0 Z$ production in $p\overline{p}$ collisions at $E_{cm} = 1.8$ TeV with $Z \rightarrow \ell\overline{\ell}$, $\nu\overline{\nu}$ and $H^0 \rightarrow b\overline{b}$. Combined with ABE 98T, a limit $\sigma(H^0 + W/Z)\cdot B(H^0 \rightarrow b\overline{b}) <$ (7.8–6.6) pb (95 %CL) for $m_{H^0} = 90$–130 GeV is derived, which is more than one order of magnitude larger than the expected Standard Model cross section.

[7] 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.

[8] 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 04,) although we do not include it in the Listings or Tables: $m_H = 114^{+69}_{-45}$ GeV. This is obtained from a fit to LEP, SLD, W mass, top mass, and neutrino scattering data available in the Summer of 2004, with $\Delta\alpha^{(5)}_{\rm had}(m_Z) = 0.0276 \pm 0.0036$. The 95%CL limit is 260 GeV.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[9] CHANOWITZ	02	RVUE	
390^{+750}_{-280}		[10] ABBIENDI	01A	OPAL	
		[11] CHANOWITZ	99	RVUE	
<290	95	[12] D'AGOSTINI	99	RVUE	
<211	95	[13] FIELD	99	RVUE	
		[14] CHANOWITZ	98	RVUE	
$170^{+150}_{-\ 90}$		[15] HAGIWARA	98B	RVUE	
$141^{+140}_{-\ 77}$		[16] DEBOER	97B	RVUE	
$127^{+143}_{-\ 71}$		[17] DEGRASSI	97	RVUE	$\sin^2\theta_W$(eff,lept)
$158^{+148}_{-\ 84}$		[18] DITTMAIER	97	RVUE	
$149^{+148}_{-\ 82}$		[19] RENTON	97	RVUE	
$145^{+164}_{-\ 77}$		[20] ELLIS	96C	RVUE	
185^{+251}_{-134}		[21] GURTU	96	RVUE	

[9] 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.

[10] 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.

[11] 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.

[12] 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.

[13] 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.

[14] 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.

[15] 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.

[16] 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). $1/\alpha(m_Z) = 128.90 \pm 0.09$ and $\alpha_s(m_Z) = 0.120 \pm 0.003$ 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.

[17] 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.

[18] 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).

[19] 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.

[20] 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.

[21] 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 $e^+e^- \rightarrow H^0_1 Z^0$ in the channels used for the Standard Model Higgs searches and $e^+e^- \rightarrow H^0_1 A^0$ 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 $m_{H_1^0}$. 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 earlier editions 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
$>$ 84.5	95	[22,23] ABBIENDI	04M	OPAL	$E_{cm} \leq 209$ GeV
$>$ 89.7	95	[22,24] ABDALLAH	04	DLPH	$E_{cm} \leq 209$ GeV, $\tan\beta > 0.4$
$>$ 86.0	95	[22,25] ACHARD	02H	L3	$E_{cm} \leq 209$ GeV, $\tan\beta > 0.4$
> 89.8	95	[22,26] HEISTER	02	ALEP	$E_{cm} \leq 209$ GeV, $\tan\beta > 0.5$
$>$100	95	[27] AFFOLDER	01D	CDF	$p\overline{p} \rightarrow b\overline{b}H_1^0$, $\tan\beta \gtrsim 55$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[28] ABBIENDI	03G	OPAL	$H_1^0 \rightarrow A^0 A^0$

[22] 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).

[23] ABBIENDI 04M exclude $0.7 < \tan\beta < 1.9$, assuming $m_t = 174.3$ GeV. Limits for other MSSM benchmark scenarios, as well as for CP violating cases, are also given.

[24] 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.

[25] 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.

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

[27] 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 $\tan\beta$, and for different stop mixing scenarios. Stronger limits are obtained at larger $\tan\beta$ values.

[28] 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
> 85.0	95	[29,30] ABBIENDI	04M	OPAL	$E_{cm} \leq 209$ GeV
> 90.4	95	[29,31] ABDALLAH	04	DLPH	$E_{cm} \leq 209$ GeV, $\tan\beta > 0.4$
> 86.5	95	[29,32] ACHARD	02H	L3	$E_{cm} \leq 209$ GeV, $\tan\beta > 0.4$
> 90.1	95	[29,33] HEISTER	02	ALEP	$E_{cm} \leq 209$ GeV, $\tan\beta > 0.5$
>100	95	[34] AFFOLDER	01D	CDF	$p\overline{p} \rightarrow b\overline{b}A^0$, $\tan\beta \gtrsim 55$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[35] ABULENCIA	06	CDF	$p\overline{p} \rightarrow H^0_{1,2}/A^0 + X$
		[36] ABAZOV	05T	D0	$p\overline{p} \rightarrow b\overline{b}H^0_{1,2}/A^0 + X$
		[37] ACOSTA	05Q	CDF	$p\overline{p} \rightarrow H^0_{1,2}/A^0 + X$
		[38] ABBIENDI	03G	OPAL	$H^0_1 \rightarrow A^0 A^0$
		[39] AKEROYD	02	RVUE	

[29] 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).

[30] ABBIENDI 04M exclude $0.7 < \tan\beta < 1.9$, assuming $m_t = 174.3$ GeV. Limits for other MSSM benchmark scenarios, as well as for *CP* violating cases, are also given.

[31] 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.

[32] 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.

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

[34] 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 $\tan\beta$, and for different stop mixing scenarios. Stronger limits are obtained at larger $\tan\beta$ values.

[35] ABULENCIA 06 search for $H^0_{1,2}/A^0$ production in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with $H^0_{1,2}/A^0 \rightarrow \tau^+\tau^-$. A region with $\tan\beta > 40$ (100) is excluded for $m_{A^0} = 90$ (170) GeV.

[36] ABAZOV 05T search for $H^0_{1,2}/A^0$ production in association with bottom quarks in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV, with the $b\overline{b}$ decay mode. A region with $\tan\beta \gtrsim 60$ is excluded for $m_{A^0} = 90$–150 GeV.

[37] ACOSTA 05Q search for $H^0_{1,2}/A^0$ production in $p\overline{p}$ collisions at $E_{cm} = 1.8$ TeV with $H^0_{1,2}/A^0 \rightarrow \tau^+\tau^-$. At $m_{A^0} = 100$ GeV, the obtained cross section upper limit is above theoretical expectation.

[38] 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.

[39] AKEROYD 02 examine the possibility of a light A^0 with $\tan\beta < 1$. 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. • • •					
none 1–55	95	[40] ABBIENDI	05A	OPAL	H_1^0, Type II model
none 3–63	95	[40] ABBIENDI	05A	OPAL	A^0, Type II model
>110.6	95	[41] ABDALLAH	05D	DLPH	$H^0 \rightarrow$ 2 jets
>112.3	95	[42] ACHARD	05	L3	invisible H^0
>104	95	[43] ABBIENDI	04K	OPAL	$H^0 \rightarrow$ 2 jets
		[44] ABDALLAH	04	DLPH	$H^0 V V$ couplings
>112.1	95	[42] ABDALLAH	04B	DLPH	Invisible H^0
>104.1	95	[45,46] ABDALLAH	04L	DLPH	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow \gamma\gamma$
		[47] ABDALLAH	04O	DLPH	$Z \rightarrow f\overline{f}H$
		[48] ABDALLAH	04O	DLPH	$e^+e^- \rightarrow H^0 Z$, $H^0 A^0$
>110.3	95	[49] ACHARD	04B	L3	$H^0 \rightarrow$ 2 jets
		[50] ACHARD	04F	L3	Anomalous coupling
		[51] ABBIENDI	03F	OPAL	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow$ any
		[52] ABBIENDI	03G	OPAL	$H_1^0 \rightarrow A^0 A^0$
>107	95	[53] ACHARD	03C	L3	$H^0 \rightarrow W W^*, Z Z^*, \gamma\gamma$
		[54] ABBIENDI	02D	OPAL	$e^+e^- \rightarrow b\overline{b}H$
>105.5	95	[45,55] ABBIENDI	02F	OPAL	$H_1^0 \rightarrow \gamma\gamma$
>105.4	95	[56] ACHARD	02C	L3	$H_1^0 \rightarrow \gamma\gamma$
>114.1	95	[42] HEISTER	02	ALEP	Invisible H^0, $E_{cm} \leq$ 209 GeV
>105.4	95	[45,57] HEISTER	02L	ALEP	$H_1^0 \rightarrow \gamma\gamma$
>109.1	95	[58] HEISTER	02M	ALEP	$H^0 \rightarrow$ 2 jets or $\tau^+\tau^-$
none 1–44	95	[59] ABBIENDI	01E	OPAL	H_1^0, Type-II model
none 12–56	95	[59] ABBIENDI	01E	OPAL	A^0, Type-II model
> 98	95	[60] AFFOLDER	01H	CDF	$p\overline{p} \rightarrow H^0 W/Z$, $H^0 \rightarrow \gamma\gamma$
>106.4	95	[42] BARATE	01C	ALEP	Invisible H^0, $E_{cm} \leq$ 202 GeV
> 89.2	95	[61] ACCIARRI	00M	L3	Invisible H^0
		[62] ACCIARRI	00R	L3	$e^+e^- \rightarrow H^0\gamma$ and/or $H^0 \rightarrow \gamma\gamma$
		[63] ACCIARRI	00R	L3	$e^+e^- \rightarrow e^+e^- H^0$
> 94.9	95	[64] ACCIARRI	00S	L3	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow \gamma\gamma$
>100.7	95	[65] BARATE	00L	ALEP	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow \gamma\gamma$
> 68.0	95	[66] ABBIENDI	99E	OPAL	$\tan\beta > 1$
> 96.2	95	[67] ABBIENDI	99O	OPAL	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow \gamma\gamma$
> 78.5	95	[68] ABBOTT	99B	D0	$p\overline{p} \rightarrow H^0 W/Z$, $H^0 \rightarrow \gamma\gamma$
		[69] ABREU	99P	DLPH	$e^+e^- \rightarrow H^0\gamma$ and/or $H^0 \rightarrow \gamma\gamma$
		[70] GONZALEZ-G..	98B	RVUE	Anomalous coupling
		[71] KRAWCZYK	97	RVUE	$(g-2)_\mu$
		[72] ALEXANDER	96H	OPAL	$Z \rightarrow H^0\gamma$
		[73] ABREU	95H	DLPH	$Z \rightarrow H^0 Z^*$, $H^0 A^0$
		[74] PICH	92	RVUE	Very light Higgs

[40] ABBIENDI 05A search for $e^+ e^- \rightarrow H_1^0 A^0$ in general Type-II two-doublet models, with decays H_1^0, $A^0 \rightarrow q\overline{q}$, gg, $\tau^+\tau^-$, and $H_1^0 \rightarrow A^0 A^0$.

[41] ABDALLAH 05D search for $e^+ e^- \rightarrow H^0 Z$ and $H^0 A^0$ with H^0, A^0 decaying to two jets of any flavor including gg. The limit is for SM $H^0 Z$ production cross section with B($H^0 \rightarrow jj$) = 1.

[42] 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] ABBIENDI 04K search for $e^+ e^- \rightarrow H^0 Z$ with H^0 decaying to two jets of any flavor including gg. The limit is for SM production cross section with B($H^0 \rightarrow jj$) = 1.

[44] 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.

[45] 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.

[46] Updates ABREU 01F.

[47] ABDALLAH 04O search for $Z \rightarrow b\overline{b}H^0$, $b\overline{b}A^0$, $\tau^+\tau^- H^0$ and $\tau^+\tau^- A^0$ in the final states $4b$, $b\overline{b}\tau^+\tau^-$, and 4τ. See paper for limits on Yukawa couplings.

[48] ABDALLAH 04O search for $e^+ e^- \rightarrow H^0 Z$ and $H^0 A^0$, with H^0, A^0 decaying to $b\overline{b}$, $\tau^+\tau^-$, or $H^0 \rightarrow A^0 A^0$ at E_{cm} = 189–208 GeV. See paper for limits on couplings.

[49] ACHARD 04B search for $e^+ e^- \rightarrow H^0 Z$ with H^0 decaying to $b\overline{b}$, $c\overline{c}$, or gg. The limit is for SM production cross section with B($H^0 \rightarrow jj$) = 1.

[50] ACHARD 04F search for H^0 with anomalous coupling to gauge boson pairs in the processes $e^+ e^- \rightarrow H^0\gamma$, $e^+ e^- H^0$, $H^0 Z$ with decays $H^0 \rightarrow f\overline{f}$, $\gamma\gamma$, $Z\gamma$, and $W^* W$ at E_{cm} = 189–209 GeV. See paper for limits.

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

[52] 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 region $m_{H_1^0}$ = 45-86 GeV and m_{A^0} = 2-11 GeV. See their Fig. 7 for the limits.

[53] ACHARD 03C search for $e^+ e^- \rightarrow ZH^0$ followed by $H^0 \rightarrow WW^*$ or ZZ^* 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($H^0 \rightarrow f\overline{f}$) = 0 for all f. For B($H^0 \rightarrow WW^*$) + B($H^0 \rightarrow ZZ^*$) = 1, $m_{H^0} > 108.1$ GeV is obtained. See fig. 6 for the limits under different BR assumptions.

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

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

[56] 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.

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

[58] 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.

[59] 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.

[60] 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($H^0 \rightarrow \gamma\gamma$)$< 1$.

[61] 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.

[62] 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.

[63] 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.

[64] 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).

[65] 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).

[66] ABBIENDI 99E search for $e^+e^- \rightarrow H^0A^0$ and H^0Z 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.

[67] 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 $\sigma(e^+e^- \rightarrow H^0Z^0)\times$B($H^0 \rightarrow \gamma\gamma)\times$B($X^0 \rightarrow f\overline{f}$) for various masses. Updates the results of ACKERSTAFF 98Y.

[68] 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.

[69] ABREU 99P search for $e^+e^- \rightarrow H^0\gamma$ with $H^0 \rightarrow b\overline{b}$ or $\gamma\gamma$, and $e^+e^- \rightarrow H^0q\overline{q}$ 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.

[70] 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.

[71] KRAWCZYK 97 analyse the muon anomalous magnetic moment in a two-doublet Higgs model (with type II Yukawa couplings) assuming no H_1^0ZZ 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.

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

[73] 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 tanβ >1, the region $m_{H^0}+m_{A^0} \lesssim 87$ GeV, m_{H^0} <47 GeV is excluded at 95% CL.

[74] 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($H^+ \to \tau^+\nu$)+B($H^+ \to c\overline{s}$)=1, and hold for all values of B($H^+ \to \tau^+\nu_\tau$), 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 $e^+e^- \to H^+H^-$ process. Limits from $b \to s\gamma$ 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*
> 74.4	95	ABDALLAH	04I	DLPH	$E_{cm} \le 209$ GeV
> 76.5	95	ACHARD	03E	L3	$E_{cm} \le 209$ GeV
> 79.3	95	HEISTER	02P	ALEP	$E_{cm} \le 209$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 92.0	95	ABBIENDI	04	OPAL	B($\tau\nu$) = 1
> 76.7	95	[75] ABDALLAH	04I	DLPH	Type I
		[76] ABBIENDI	03	OPAL	$\tau \to \mu\overline{\nu}\nu$, $e\overline{\nu}\nu$
		[77] ABAZOV	02B	D0	$t \to bH^+$, $H \to \tau\nu$
		[78] BORZUMATI	02	RVUE	
		[79] ABBIENDI	01Q	OPAL	$B \to \tau\nu_\tau X$
		[80] BARATE	01E	ALEP	$B \to \tau\nu_\tau$
>315	99	[81] GAMBINO	01	RVUE	$b \to s\gamma$
		[82] AFFOLDER	00I	CDF	$t \to bH^+$, $H \to \tau\nu$
> 59.5	95	ABBIENDI	99E	OPAL	$E_{cm} \le 183$ GeV

		[83] ABBOTT	99E	D0	$t \to bH^+$
		[84] ACKERSTAFF	99D	OPAL	$\tau \to e\nu\nu, \mu\nu\nu$
		[85] ACCIARRI	97F	L3	$B \to \tau\nu_\tau$
		[86] AMMAR	97B	CLEO	$\tau \to \mu\nu\nu$
		[87] COARASA	97	RVUE	$B \to \tau\nu_\tau X$
		[88] GUCHAIT	97	RVUE	$t \to bH^+$, $H \to \tau\nu$
		[89] MANGANO	97	RVUE	$B_{u(c)} \to \tau\nu_\tau$
		[90] STAHL	97	RVUE	$\tau \to \mu\nu\nu$
>244	95	[91] ALAM	95	CLE2	$b \to s\gamma$
		[92] BUSKULIC	95	ALEP	$b \to \tau\nu_\tau X$

[75] ABDALLAH 04I search for $e^+e^- \to H^+H^-$ with $H^\pm$ decaying to $\tau\nu$, cs, or $W^* A^0$ in Type-I two-Higgs-doublet models.

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

[77] 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.

[78] 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.

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

[80] 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).

[81] 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.

[82] 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.

[83] 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.

[84] 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.

[85] 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.

[86] 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 $m_{H^+} > 0.97 \tan\beta$ GeV (90% CL).

[87] COARASA 97 reanalyzed the constraint on the ($m_{H^\pm}$,$\tan\beta$) 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.

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

[89] 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.
[90] 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.
[91] 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.
[92] BUSKULIC 95 give a limit $m_{H^+} > 1.9\ \tan\beta$ 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)

This section covers searches for a doubly-charged Higgs boson with couplings to lepton pairs. Its weak isospin T_3 is thus restricted to two possibilities depending on lepton chiralities: $T_3(H^{\pm\pm}) = \pm1$, with the coupling $g_{\ell\ell}$ to $\ell^-_L \ell'^-_L$ and $\ell^+_R \ell'^+_R$ ("left-handed") and $T_3(H^{\pm\pm}) = 0$, with the coupling to $\ell^-_R \ell'^-_R$ and $\ell^+_L \ell'^+_L$ ("right-handed"). These Higgs bosons appear in some left-right symmetric models based on the gauge group SU(2)$_L\times$SU(2)$_R\times$U(1). These two cases are listed separately in the following. Unless noted, one of the lepton flavor combinations is assumed to be dominant in the decay.

LIMITS for $H^{\pm\pm}$ with $T_3 = \pm1$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
>118.4	95	[93] ABAZOV	04E	D0	$\mu\mu$
>136	95	[94] ACOSTA	04G	CDF	$\mu\mu$
> 98.1	95	[95] ABDALLAH	03	DLPH	$\tau\tau$
> 99.0	95	[96] ABBIENDI	02C	OPAL	$\tau\tau$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>133	95	[97] ACOSTA	05L	CDF	stable
		[98] ABBIENDI	03Q	OPAL	$E_{cm} \le$ 209 GeV, single $H^{\pm\pm}$
		[99] GORDEEV	97	SPEC	muonium conversion
		[100] ASAKA	95	THEO	
> 45.6	95	[101] ACTON	92M	OPAL	
> 30.4	95	[102] ACTON	92M	OPAL	
none 6.5–36.6	95	[103] SWARTZ	90	MRK2	

[93] ABAZOV 04E search for $H^{++}H^{--}$ pair production in $H^{\pm\pm} \to \mu^\pm\mu^\pm$. The limit is valid for $g_{\mu\mu} \gtrsim 10^{-7}$.
[94] ACOSTA 04G search for $H^{++}H^{--}$ pair production in $p\overline{p}$ collisions with muon and electron final states.The limit holds for $\mu\mu$. For ee and $e\mu$ modes, the limits are 133 and 115 GeV, respectively. The limits are valid for $g_{\ell\ell'} \gtrsim 10^{-5}$.
[95] ABDALLAH 03 search for $H^{++}H^{--}$ pair production either followed by $H^{++} \to \tau^+\tau^+$, or decaying outside the detector.
[96] 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 $g(H\ell\ell) \gtrsim 10^{-7}$.

[97] ACOSTA 05L search for $H^{++}H^{--}$ pair production in $p\overline{p}$ collisions. The limit is valid for $g_{\ell\ell'} < 10^{-8}$ so that the Higgs decays outside the detector.

[98] ABBIENDI 03Q searches for single $H^{\pm\pm}$ via direct production in $e^+e^- \rightarrow e^\pm e^\pm H^{\mp\mp}$, and via t-channel exchange in $e^+e^- \rightarrow e^+e^-$. In the direct case, and assuming B($H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm$) = 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).

[99] 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.

[100] 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.

[101] 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.

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

[103] 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.

LIMITS for $H^{\pm\pm}$ with $T_3 = 0$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
> 98.2	95	[104] ABAZOV	04E	D0	$\mu\mu$
>113	95	[105] ACOSTA	04G	CDF	$\mu\mu$
> 97.3	95	[106] ABDALLAH	03	DLPH	$\tau\tau$
> 97.3	95	[107] ACHARD	03F	L3	$\tau\tau$
> 98.5	95	[108] ABBIENDI	02C	OPAL	$\tau\tau$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>109	95	[109] ACOSTA	05L	CDF	stable
		[110] ABBIENDI	03Q	OPAL	$E_{cm} \leq 209$ GeV, single $H^{\pm\pm}$
		[111] GORDEEV	97	SPEC	muonium conversion
> 45.6	95	[112] ACTON	92M	OPAL	
> 25.5	95	[113] ACTON	92M	OPAL	
none 7.3–34.3	95	[114] SWARTZ	90	MRK2	

[104] ABAZOV 04E search for $H^{++}H^{--}$ pair production in $H^{\pm\pm} \rightarrow \mu^\pm\mu^\pm$. The limit is valid for $g_{\mu\mu} \gtrsim 10^{-7}$.

[105] ACOSTA 04G search for $H^{++}H^{--}$ pair production in $p\overline{p}$ collisions with muon and electron final states. The limit holds for $\mu\mu$.

[106] ABDALLAH 03 search for $H^{++}H^{--}$ pair production either followed by $H^{++} \rightarrow \tau^+\tau^+$, or decaying outside the detector.

[107] ACHARD 03F search for $e^+e^- \rightarrow H^{++}H^{--}$ with $H^{\pm\pm} \rightarrow \ell^\pm\ell'^\pm$. The limit holds for $\ell = \ell' = \tau$, and slightly different limits apply for other flavor combinations. The limit is valid for $g_{\ell\ell'} \gtrsim 10^{-7}$.

[108] 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 $g(H\ell\ell) \gtrsim 10^{-7}$.

[109] ACOSTA 05L search for $H^{++} H^{--}$ pair production in $p\overline{p}$ collisions. The limit is valid for $g_{\ell\ell'} < 10^{-8}$ so that the Higgs decays outside the detector.

[110] ABBIENDI 03Q searches for single $H^{\pm\pm}$ via direct production in $e^+ e^- \rightarrow e^\pm e^\pm H^{\mp\mp}$, and via t-channel exchange in $e^+ e^- \rightarrow e^+ e^-$. In the direct case, and assuming $B(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 1$, 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).

[111] 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.

[112] 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.

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

[114] 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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