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].

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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 $\Lambda_{\mathrm{GUT}} \approx 10^{16}$ 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 Λ_{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] $\sigma^{\mathrm{SM}}_{HZ}$ 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 $p\bar{p}H^0$). At the Tevatron and for masses less than about 140 GeV (where the Higgs boson mainly decays to $b\bar{b}$), the most promising discovery channels are WH^0 and ZH^0 with $H^0 \to b\bar{b}$ ($H^0 \to W^*W$ 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 $t\bar{t}H^0 \to t\bar{t}b\bar{b}$ 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.

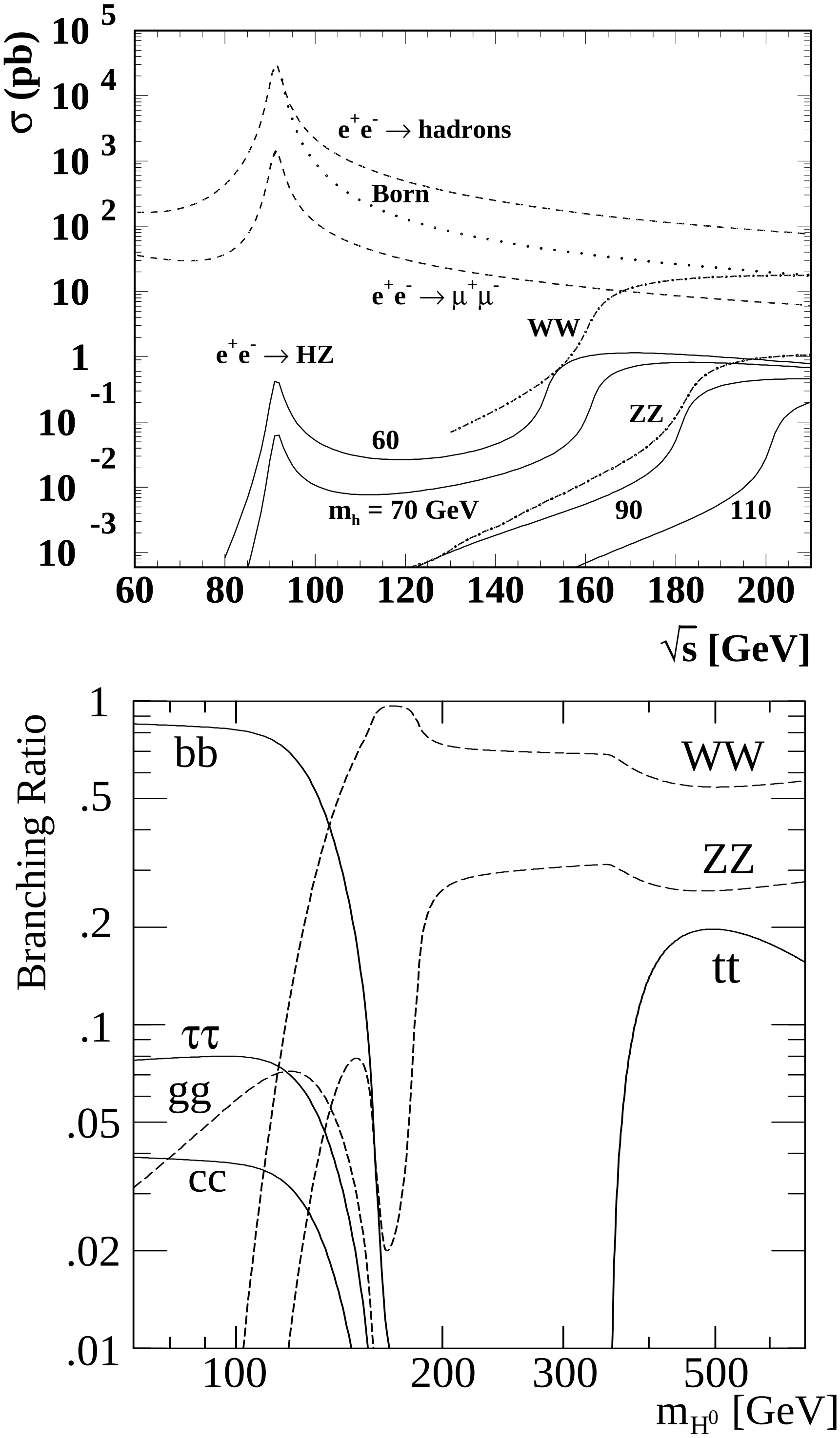


Figure 1: Cross sections, as a function of $\sqrt{s}$, for the Higgs-strahlung process in the SM for fixed values of m_{H^0} (full lines) and for other SM processes which contribute to the background; Bottom: Branching ratios for the main decay modes of the SM Higgs boson (from Ref. 10).

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 $H^0 \to b\bar{b}$ has the largest branching ratio. Decays to $\tau^+\tau^-$, $c\bar{c}$, 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 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 $e^+e^- \to W^+W^-$ events. At LEP2, the composition of the background is more complex than at LEP1, due to the four-fermion processes $e^+e^- \to W^+W^-$ 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 $e^+e^- \to (H^0 \to b\bar{b})(Z^0 \to q\bar{q})$ 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 $e^+e^- \to (H^0 \to b\bar{b})(Z^0 \to \nu\bar{\nu})$ 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, $e^+e^- \to (H^0 \to b\bar{b})(Z^0 \to e^+e^-$, $\mu^+\mu^-)$, the two leptons reconstruct to M_Z, and the two jets have

b 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 $1 - CL_b = 1 - \mathcal{P}_b(Q \leq Q_{\text{observed}})$ 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 [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, $p\overline{p} \rightarrow VH^0$ ($V \equiv Z^0$, $W^{\pm}$), 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 $H^0 \rightarrow W^*W$ channel and using Run II data of about 118 pb^{-1}, have been reported [29].

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.

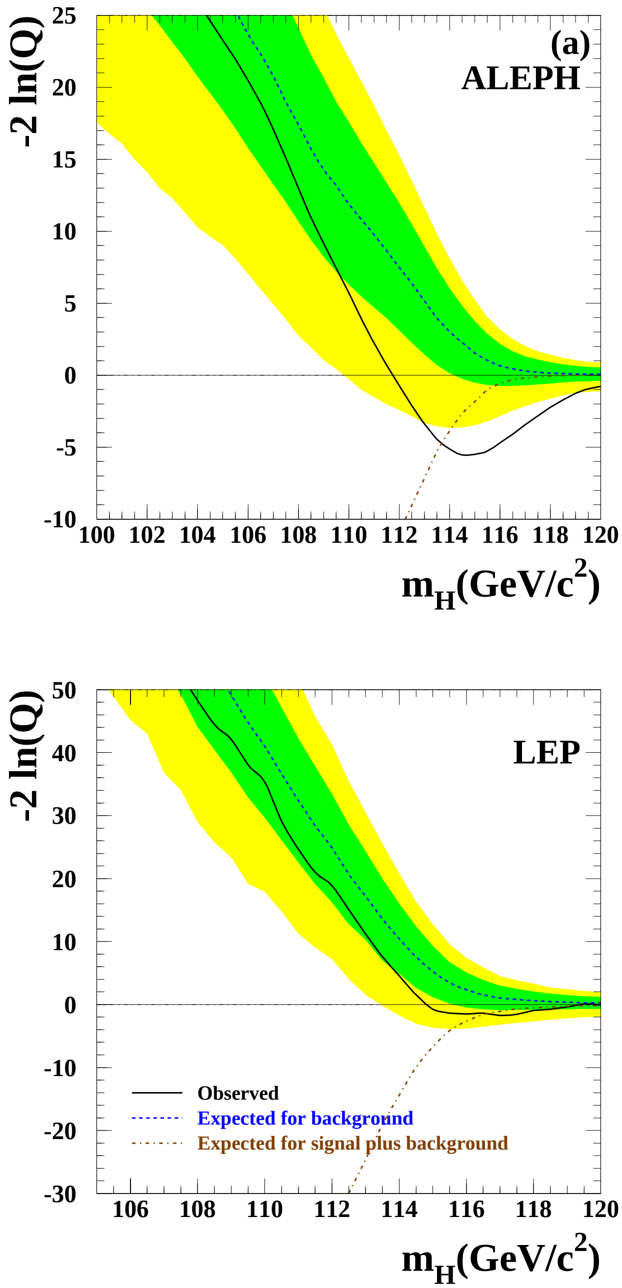


Figure 2: Observed (solid line), and expected behaviors of the test statistic $-2\ln Q$ for the background (dashed line), and the signal + background hypothesis (dash-dotted line) as a function of the test mass m_H. Top: ALEPH data alone; bottom: LEP data combined [27]. The dark and light shaded areas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

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

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

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

with the kinematic factor

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

and $\lambda_{ij} = [1-(m_i+m_j)^2/s][1-(m_i-m_j)^2/s]$. 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 $p\overline{p} \to (h^0$ 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.

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 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 $b\bar{b}$ and $\tau^+\tau^-$ pairs are preferred, with branching ratios of about 90% and 8%, while the decays to $c\bar{c}$ and gluon pairs are suppressed. Decays to $c\bar{c}$ may become important for $\tan\beta < 1$. The decay $h^0 \rightarrow A^0A^0$ 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)

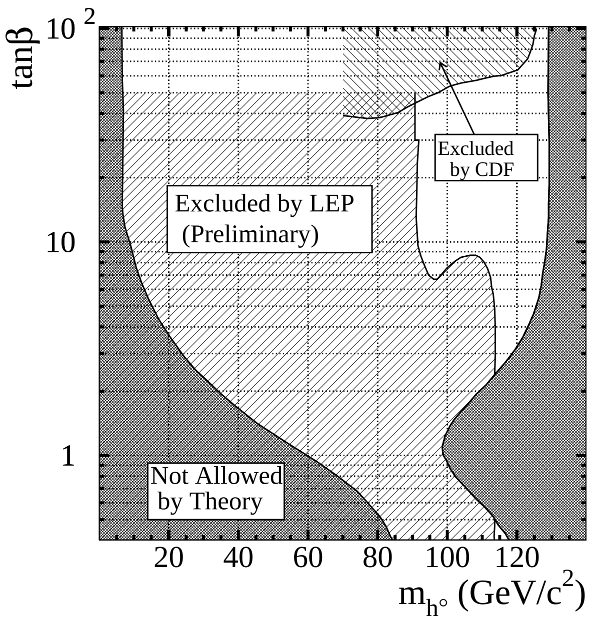
The searches at LEP address the Higgs-strahlung process $e^+e^- \rightarrow h^0Z^0$ and the pair production process $e^+e^- \rightarrow h^0A^0$, and exploit the complementarity of the two cross sections. The results for h^0Z^0 are obtained by re-interpreting the SM Higgs searches, taking into account the MSSM reduction factor $\sin^2(\beta-\alpha)$. Those for h^0A^0 are obtained from specific searches for $(b\bar{b})(b\bar{b})$ and $(\tau^+\tau^-)(q\bar{q})$ 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 $b\overline{b}b\overline{b}$, $b\overline{b}\tau^+\tau^-$, 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.



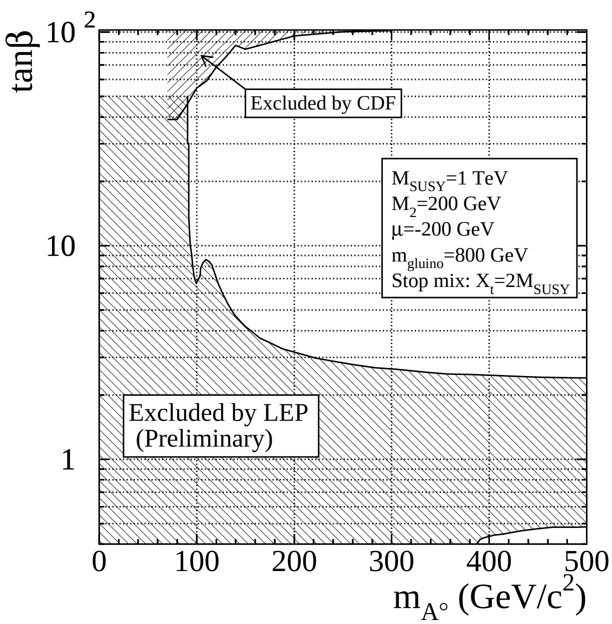


Figure 3: The 95% CL bounds on m_{h^0}, m_{A^0} and $\tan\beta$ for the m_{h^0}-*max* benchmark scenario, from LEP [37]. The exclusions at large $\tan\beta$ from CDF [39] are also indicated.

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 $H_i \quad (i = 1, 2, 3)$ 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, $e^+e^- \to H_i H_j \;\; (i \neq j)$. 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]

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

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

(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

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

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

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,

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

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 $b\bar{b}$ 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 $b\bar{b}$.

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 $M_{\rm SUSY}$ (*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

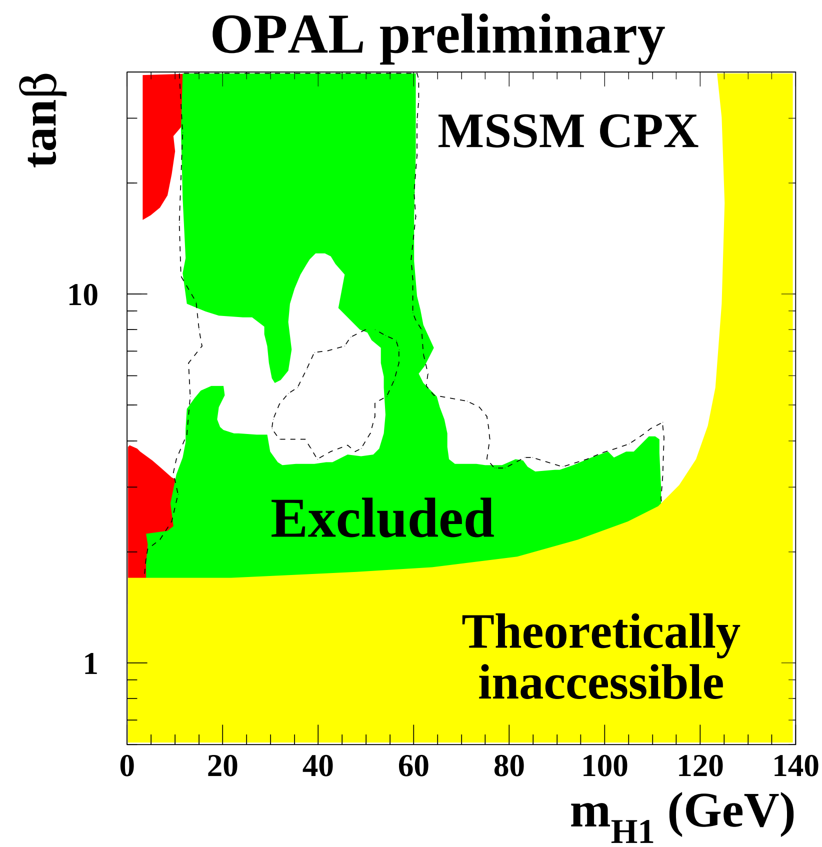


Figure 4: The 95% CL bounds on m_{H_1} and $\tan\beta$ in the CPX MSSM scenario with $\mu =$ 2 TeV and $M_{\rm SUSY} = 500$ GeV, from a preliminary OPAL analysis [36]. The shaded areas are excluded either by the model or by the experiment. The areas delimited by the dashed lines are expected to be excluded 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.

dependent. In 2HDM of "type 2,"* and for masses which are accessible at LEP energies, the decays $H^+ \rightarrow c\overline{s}$ and $\tau^+\nu$

* 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.

dominate. The final states $H^+H^- \rightarrow (c\overline{s})(\overline{c}s)$, $(\tau^+\nu_\tau)(\tau^-\overline{\nu}_\tau)$, and $(c\overline{s})(\tau^-\overline{\nu}_\tau)+(\overline{c}s)(\tau^+\nu_\tau)$ are therefore considered, and the results are presented with the $H^+ \rightarrow \tau^+\nu$ decay branching ratio as a free parameter.

At LEP2 energies, the background process $e^+e^- \rightarrow W^+W^-$ constrains the search sensitivity essentially to $m_{H^\pm}$ less than 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 $H^+ \rightarrow \tau^+\nu$ 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 $H^\pm \rightarrow W^{(\pm *)}A^0$ 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 $t \rightarrow bH^+$ would then compete with the SM process $t \rightarrow bW^+$, 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 $t \rightarrow bW^+$, and a direct search for $t \rightarrow bH^+ \rightarrow b\tau^+\nu_\tau$ [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 $t \rightarrow bH^+$ [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 $b \rightarrow s\gamma$ to the SM prediction. In the SM, this process is mediated by virtual W exchange [49], while in the 2HDM of "type 2," the branching ratio is altered by

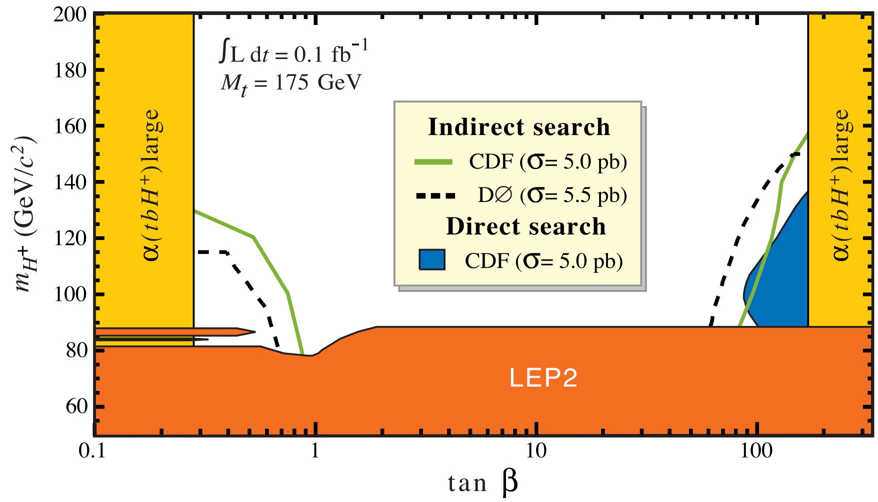


Figure 5: Summary of the 95% CL exclusions in the (m_{H^+}, $\tan\beta$) plane from DØ [45] and CDF [47], using various indirect and direct observation techniques (the regions below the curves are excluded). The two experiments use slightly different theoretical $t\bar{t}$ cross sections, as indicated.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

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 $Z^0 \rightarrow H^{++}H^{--}$ 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 $e^+e^- \rightarrow h^0Z^0$, 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 $e^+e^- \rightarrow h^0Z^0$ 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 $b\bar{b}$. 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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