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).

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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 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 $m_{H^0} = 91^{+45}_{-32}$ 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 $H^0 \rightarrow b\bar{b}$ 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 $mh^0 = 500$ GeV.

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

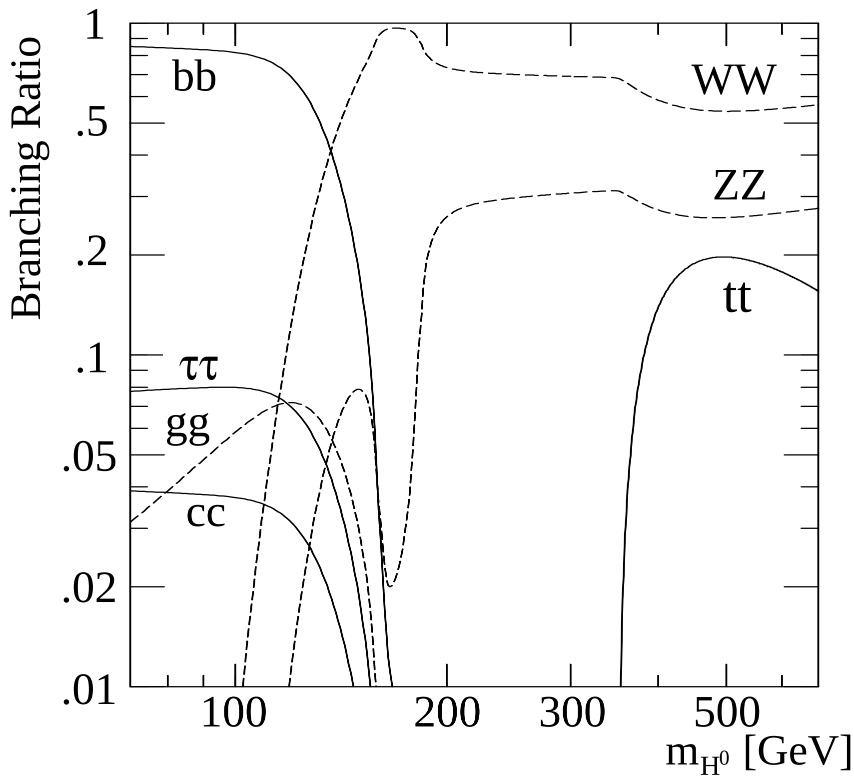

Figure 1: Branching ratios for the main decays of the SM Higgs boson (from Ref. 10).

fusion channels $gg \to H^0 \to \gamma\gamma$, W^+W^-, Z^0Z^0, the associated production channel $t\bar{t}H^0 \to t\bar{t}b\bar{b}$ 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 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 $e^+e^- \to (H^0 \to b\bar{b})\ (Z^0 \to q\bar{q})$ 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 $e^+e^- \to (H^0 \to b\overline{b})(Z^0 \to \nu\overline{\nu})$ 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, $e^+e^- \to (H^0 \to b\overline{b})(Z^0 \to e^+e^-, \mu^+\mu^-)$, the two leptons reconstruct to M_Z, and the two jets have b-flavor. Although the branching ratio is small (only about 6%), this channel adds significantly to the overall search sensitivity, since it has low background.
- Final states with tau leptons are produced in the processes $e^+e^- \to (H^0 \to \tau^+\tau^-)(Z^0 \to q\overline{q})$ and $(H^0 \to q\overline{q})(Z^0 \to \tau^+\tau^-)$; they occur with a branching ratio of about 10% in total.

At LEP1, only the missing energy and leptonic final states could be used in the search for the SM Higgs boson, because of prohibitive backgrounds in the other channels; at LEP2 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, $e^+e^- \to$ 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 $1 - CL_b = 1 - \mathcal{P}_b(Q \le Q_{\text{observed}})$ and $CL_{s+b} = \mathcal{P}_{s+b}(Q \le Q_{\text{observed}})$, 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.

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

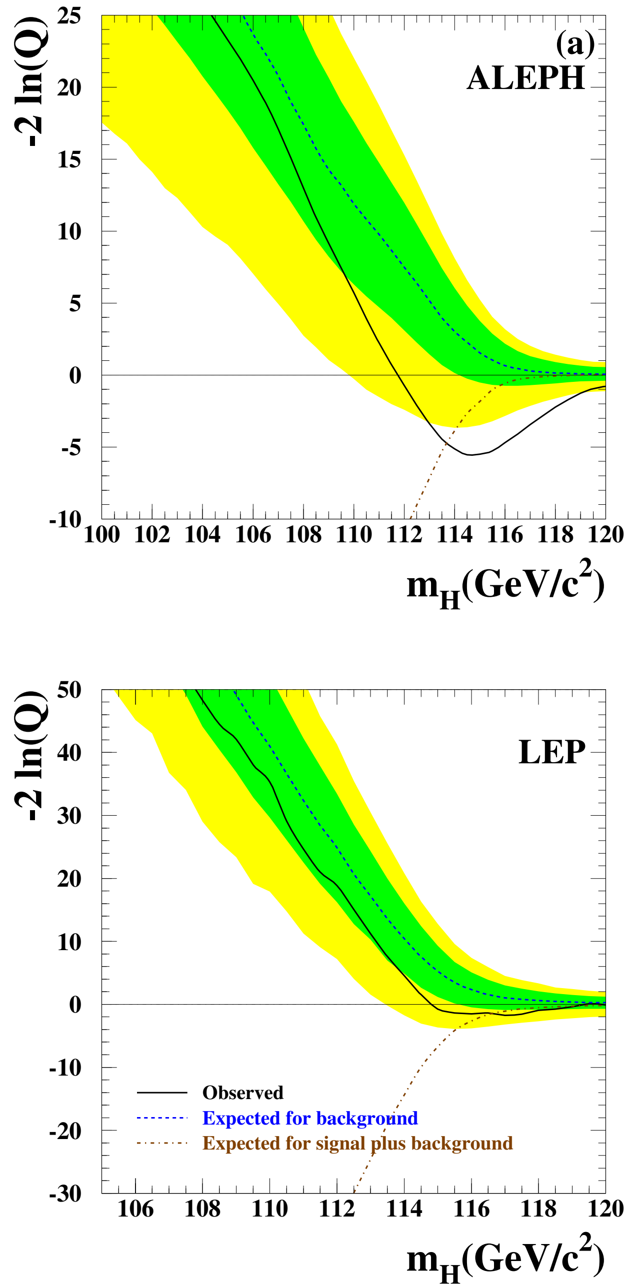

Figure 2: Observed (solid line), and expected behaviors of the test statistic $-2\ln Q$ for the background (dashed line), and the signal + background hypothesis (dash-dotted line) as a function of the test mass m_H. Left: ALEPH data alone; right: LEP data combined. The dark and light shaded areas represent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

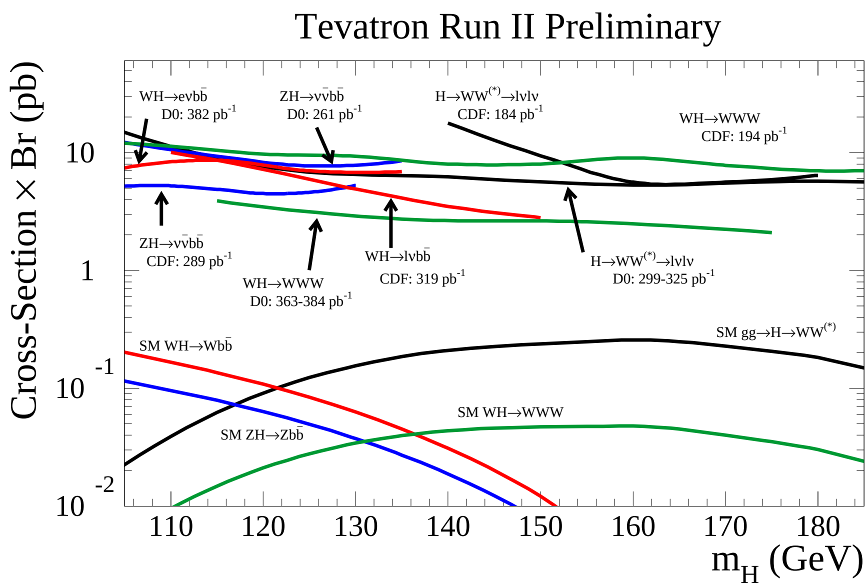

Figure 3: Upper bounds, obtained by the Tevatron experiments CDF and D0, for the cross-sections of event topologies motivated by Higgs boson production in the SM. The curves in the opper part represent the 95% CL experimental limits; the curves in the lower part are the SM predictions (from Ref. 30).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

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.

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 $e^+e^- \to h^0Z^0$, 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 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

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

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 $b\bar{b}$ and $\tau^+\tau^-$ pairs are preferred, with branching ratios of about 90% and 8%. Decays to $c\bar{c}$ and gluon pairs may become important for $\tan\beta < 1$ or for particular parameter choices where the decays to $b\bar{b}$ 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 re-interpreted, taking into account the MSSM reduction factor $\sin^2(\beta-\alpha)$; for pair production, searches are performed specifically for the $(b\bar{b})(b\bar{b})$ and $(\tau^+\tau^-)(q\bar{q})$ 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 $M_{\rm SUSY}$ 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 $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, 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

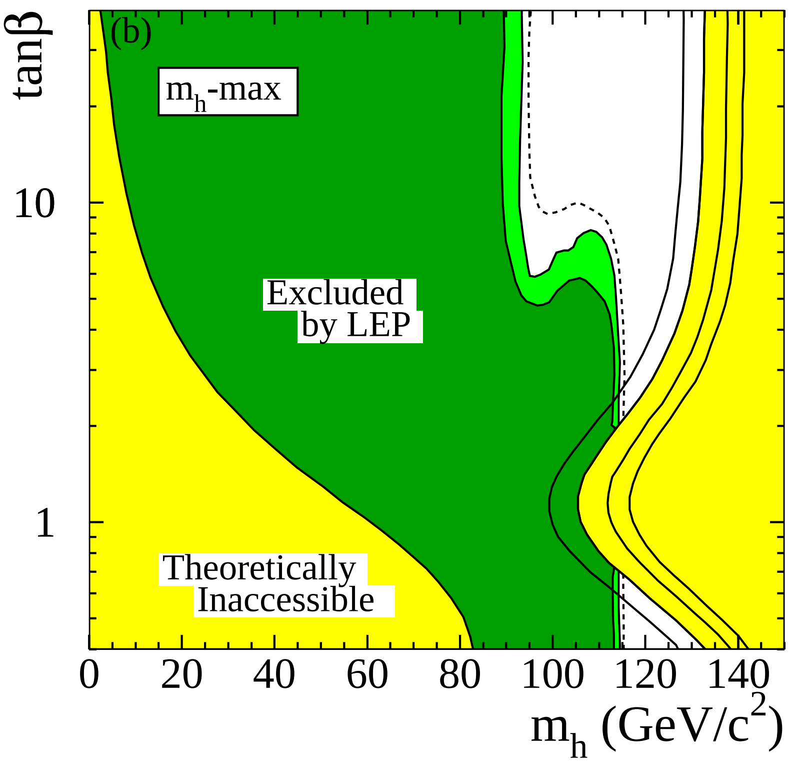

Figure 4: The MSSM exclusion limits, at 95% CL (light-green) and 99.7% CL (dark-green), obtained by LEP for the m_{h_0}-*max* benchmark scenario, with $m_t = 174.3$ GeV. The figure shows the excluded and theoretically inaccessible regions in the $(m_{h_0}, \tan\beta)$ projection. The upper edge of the parameter space is sensitive to the top quark mass; it is indicated, from left to right, for $m_t = 169.3$, 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.

on searches for neutral Higgs bosons produced in association with bottom quarks and decaying into $b\bar{b}$ [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.

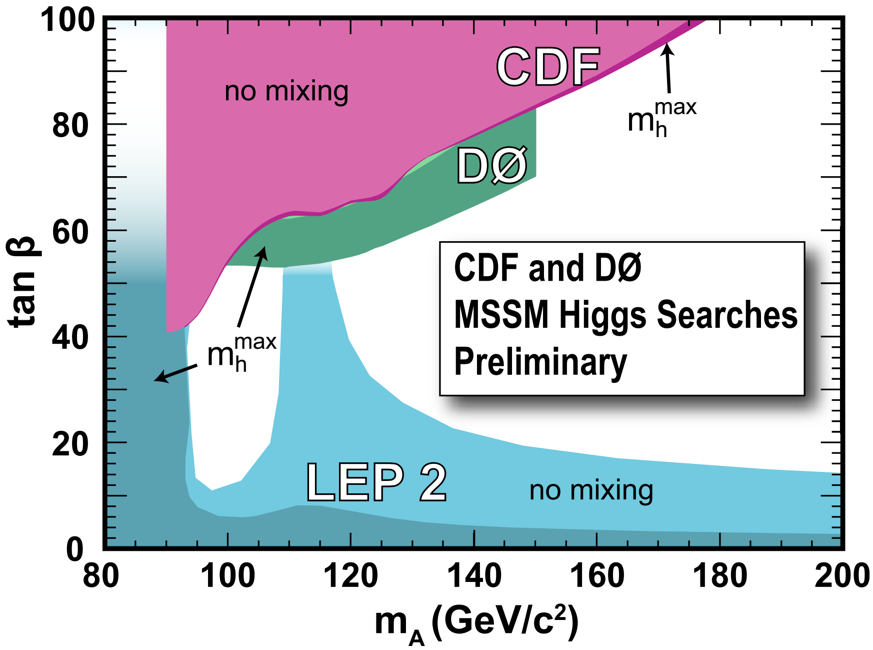

Figure 5: The MSSM exclusion limits, at 95% CL obtained by the Tevatron experiments CDF and D0, and by LEP, for the *no-mixing* (light color shadings) and the $m_{H^0} - max$ (darker color shadings) benchmark scenarios, projected onto the $(m_{A^0}, \tan\beta)$ plane of the parameter space. CDF uses 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]

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

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

(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

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

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

obey 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

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

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

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.

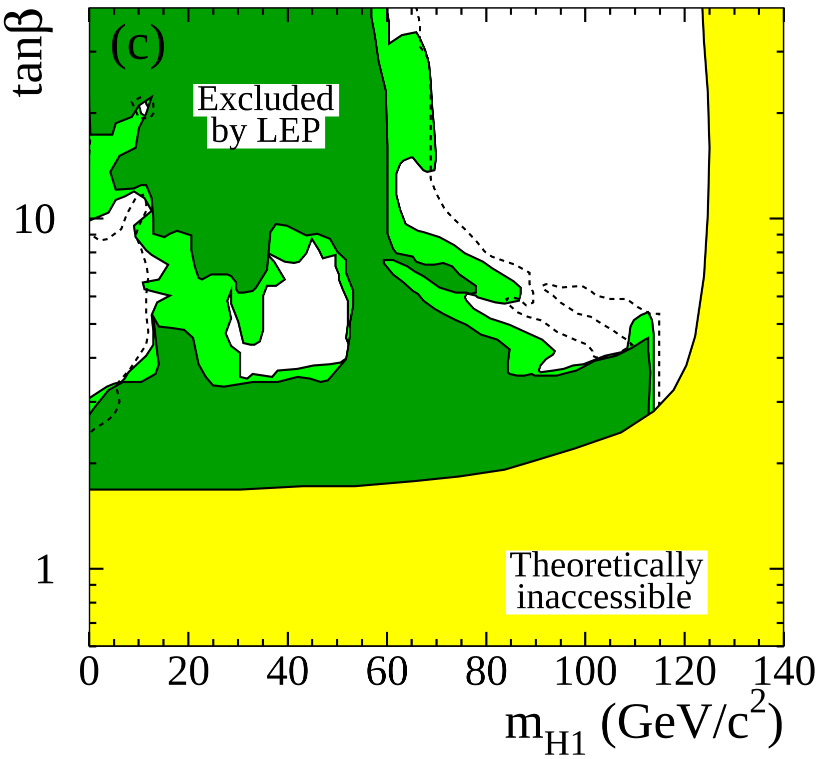

Figure 6: The MSSM exclusion limits, at 95% CL (light-green) and 99.7% CL (dark-green), obtained by LEP for a CP-violating scenario with $\mu = 2$ TeV and $M_{SUSY} = 500$ GeV, and with $m_{\rm t} = 174.3$ GeV. The figure shows the excluded and theoretically inaccessible regions in the $(m_{\rm H_1}, \tan\beta)$ 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.

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] 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 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 $t\bar{t}$ cross section measurements in the di-lepton, lepton+jet and lepton+($\tau \to$ hadrons) event

[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.

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.

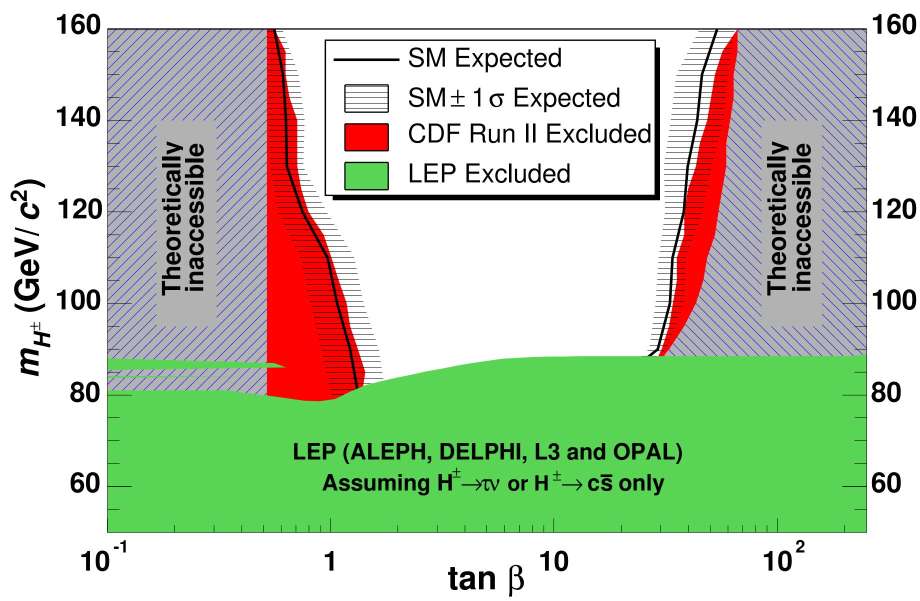

Figure 7: Summary of the 95% CL exclusions in the (m_{H^+}, $\tan\beta$) plane obtained by LEP [48] and CDF. The size of the data sample used by CDF, the choice of the top quark mass, and the soft SUSY breaking parameters to which the CDF exclusions apply, are indicated in the figure. The full lines 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 $b \to s\gamma$ 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 $e^+e^+e^-e^-$ and $e^+\mu^+e^-\mu^-$ [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.

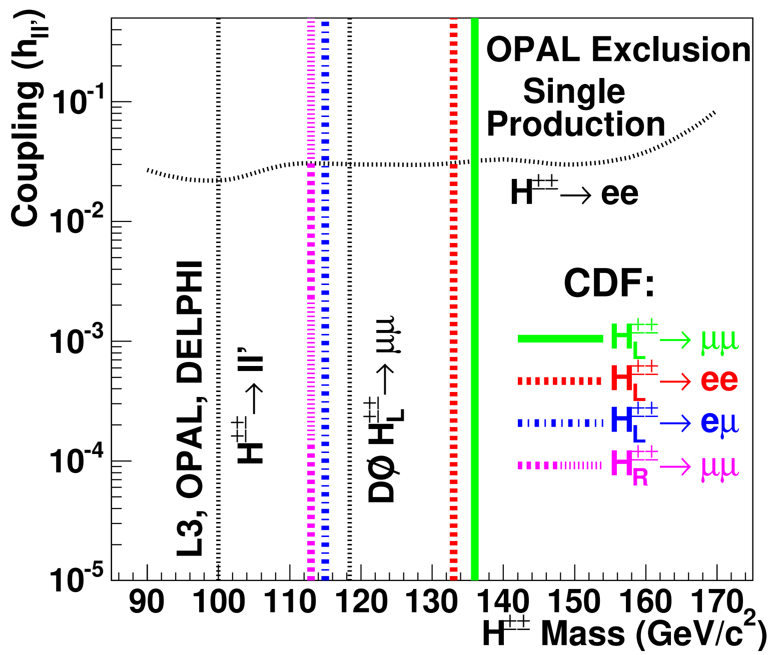

Figure 8: The 95% c.l. exclusion limits on the couplings to leptons of right- and left-handed doubly-charged Higgs bosons, obtained by LEP and Tevatron experiments (from Ref. 63). See full-color version on color pages at end of book.

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 $e^+e^- \to S^0 Z^0$ [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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