HIGGS SEARCH RESULTS

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ABSTRACT

This paper shortly reports on the results of Higgs boson searches performed at LEP and Tevatron. No signal is found and limits on the mass and couplings of the Higgs boson are derived. Interpreting the data in the framework of the Standard Model, the 95% C.L. lower limit of 114.4 GeV on the Higgs boson mass is obtained.

1 Introduction

The Standard Model (SM) [1] of electroweak interactions is a well established theory which has been very successful in accounting for various experimental observations as well as in its predictions of new physics phenomena. The unproven keystone of the SM is the mechanism of mass generation. The most favored one is the so-called Higgs mechanism [2]. A doublet of scalar complex fields with non-zero vacuum expectation value is postulated, breaking electroweak symmetry and generating weak boson and fermion masses. The Higgs mechanism gives rise to one more physical state − the Higgs boson. The discovery of this particle would be a crucial step in establishing the mechanism of electroweak symmetry breaking and in our understanding of the origin of mass. One Higgs doublet is the minimum which is required to generate weak boson and fermion masses. There are extensions of the SM postulating additional Higgs multiplets and thus predicting a spectrum of physical Higgs particles [3]. Over the last decade searches for Higgs bosons of various theoretical models have been performed at the Tevatron $\mathrm{p\bar{p}}$ collider and the Large Electron-Positron (LEP) collider. The results of these searches are reviewed.

2 The Standard Model Higgs Boson

2.1 Search for the SM Higgs Boson at LEP

Over the last three years of LEP running, the four LEP collaborations, ALEPH, DELPHI, L3 and OPAL, have collected 2460 pb^{-1} of data at center-of-mass energies between 189 and 209 GeV with about 530 pb^{-1} above 206 GeV. These data provided sensitivity to the SM Higgs boson up to a mass of $\mathrm{m_H} \sim 115$ GeV.

At LEP, the production of the Higgs boson is expected mainly via the Higgs-strahlung process, $\mathrm{e^+e^-} \to \mathrm{Z^*} \to \mathrm{HZ}$. The processes of WW and ZZ fusion, giving rise to the $\mathrm{H}\nu\bar{\nu}$ and $\mathrm{He^+e^-}$ final states, contribute with a smaller rates to the Higgs boson production. The dependence of the production cross sections on the Higgs boson mass at a typical LEP energy, attained in the year 2000, is illustrated in Figure 1 (left). The SM Higgs boson decay branching fractions as a function of the Higgs boson mass are displayed in Figure 1 (right).

The search for the SM Higgs boson is based on the study of four distinct topologies, arising from the Higgs-strahlung process: $\mathrm{HZ} \to \mathrm{q\bar{q}q\bar{q}}$ (four-jet channel); $\mathrm{HZ} \to \mathrm{q\bar{q}}\nu\bar{\nu}$ (missing energy channel); $\mathrm{HZ} \to \mathrm{q\bar{q}}\ell^+\ell^-(\ell = \mathrm{e}, \mu)$ (semileptonic channel) and $\mathrm{HZ} \to \mathrm{q\bar{q}}\tau^+\tau^-, \tau^+\tau^-\mathrm{q\bar{q}}$ (tau channels). Searches in channels with hadronic decays of the Higgs boson are optimized for the $\mathrm{H} \to \mathrm{b\bar{b}}$ decay mode, which is pre-

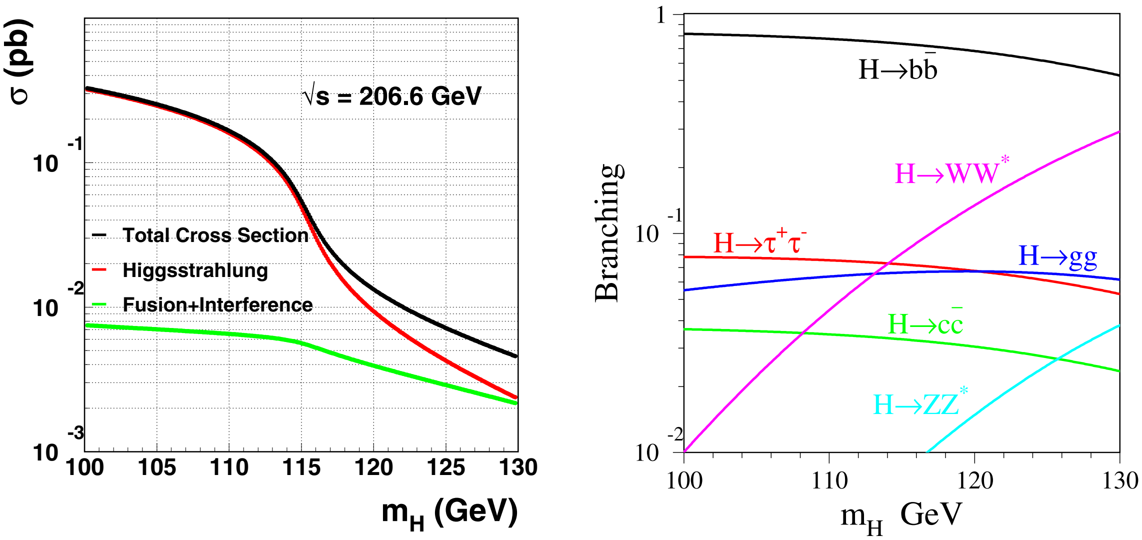

Figure 1: The production and decays of the SM Higgs boson. Left: the cross sections of the production mechanisms at LEP at $\sqrt{s} = 206.6$ GeV as a function of m_H. Right: the decay branching fractions as a function of m_H.

dicted to be dominant in the mass range accessible at LEP. Hence, tagging b quarks plays a crucial role in identification of signal events. The main processes contributing to the background for the Higgs boson searches are: quark antiquak pair production with possible initial state radiation, $e^+e^- \to q\bar{q}(\gamma)$, pair-wise production of W bosons, $e^+e^- \to W^+W^-$, pair-wise production of Z bosons, $e^+e^- \to ZZ$, single W boson production, $e^+e^- \to We\nu$, and single Z boson production, $e^+e^- \to Ze^+e^-$.

The results of the individual analyses are expressed in terms of one (or more) final variable, also called *discriminant*. It is constructed, exploiting event features, which discriminate between background and signal. Among them are the invariant mass of the two jets (or two tau leptons) assumed to stem from the Higgs boson, hereafter called the reconstructed Higgs boson mass, m_H^{rec}, b-tag variable, quantifying the probability for an event to contain b jets, and topological characteristics of an event. As an example, Figure 2 shows the distribution of m_H^{rec} after combining data from all four experiments in all search channels. The final variable, built in the same way for data, Monte Carlo background and Monte Carlo signal samples, is then used to evaluate on statistical basis the presence of a signal in data.

An excess of 3σ beyond background expectation compatible with the production of the Higgs boson with the mass near 115 GeV is reported by ALEPH

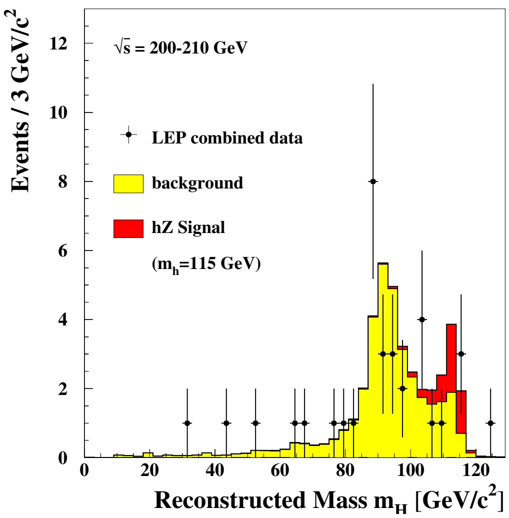

Figure 2: Distribution of the reconstructed Higgs boson mass, m_H^{rec}, obtained with a special, non-biasing, selection. The cuts are adjusted in such a way as to obtain approximately equal numbers of expected signal and expected background events in the region $m_H^{rec} > 109$ GeV.

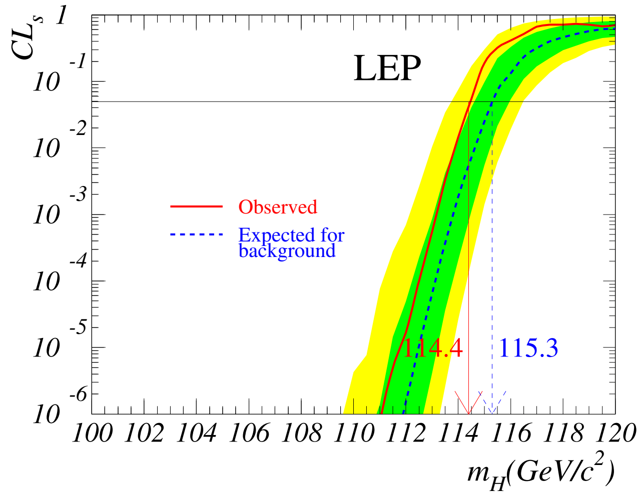

Figure 3: Confidence level CL_s as a function of the tested Higgs boson mass. The solid line: observation; the dashed line: expectation in the absence of a signal. The shaded areas represent 1σ and 2σ bands centered on the value expected in the absence of a signal. Results from the four LEP collaborations are combined.

collaboration [4]. This effect comes from events of the $HZ \to q\bar{q}q\bar{q}$ topology and is not confirmed neither by other search channels nor by other LEP collaborations [5]. In the LEP combined search, the excess is diminished down to about 1.7σ [6] due to background-like observations by the other experiments. The LEP combined data are used to set a lower limit on the Higgs boson mass. Figure 3 shows the dependence of the confidence level CL_s, used to exclude the signal hypothesis, on the tested Higgs boson mass. An observation of the CL_s value smaller than 5% means that the signal hypothesis is ruled out at 95% C.L.. A lower limit of 114.4 GeV on the mass of the SM Higgs boson is derived at 95% C.L..

2.2 Searches for the SM Higgs Boson at Tevatron

The searches for the SM Higgs boson are performed by the CDF and D0 collaborations [7] using about 0.1 fb^{-1} of data collected per experiment at center-of-mass energy $\sqrt{s} = 1.8$ TeV during the RunI data taking period at Tevatron.

Although single Higgs boson production via gluon fusion, $gg \to H$, has the highest cross-section, the more promising channels for the SM Higgs boson search are $q\bar{q}' \to HW$ and $q\bar{q} \to HZ$ production, since a large fraction of copious QCD background can be suppressed by tagging leptons originating from decays of W or Z bosons. The Higgs boson is searched for by its decay into $b\bar{b}$. Four final states are studied: $HZ \to b\bar{b}\ell^+\ell^-(\ell = e, \mu)$; $HZ \to b\bar{b}\nu\bar{\nu}$; $HW \to b\bar{b}\ell\nu(\ell = e, \mu)$ and $HZ(HW) \to b\bar{b}q\bar{q}$. Data are found to agree with the SM background predictions. However, the sensitivity of this search does not reach the SM expectations for a signal: the 95% C.L. upper limit on the quantity $\sigma(p\bar{p} \to HV) \times Br(H \to b\bar{b})$ (where V stands for W and Z) is larger than the values predicted by the SM, as can be seen in Figure 4. Hence, a mass limit cannot be derived.

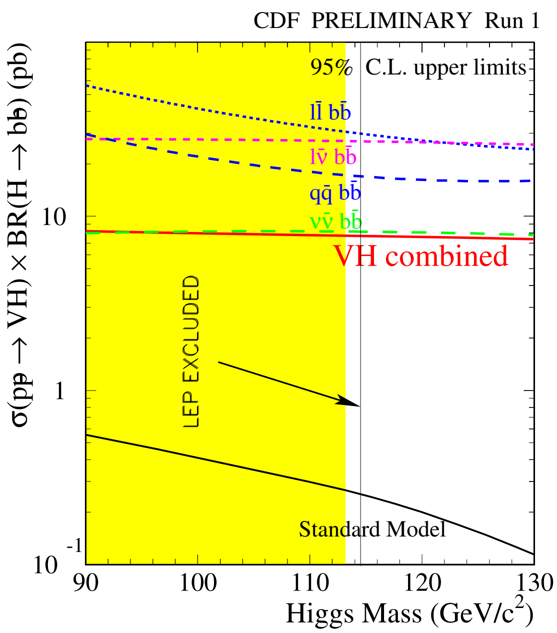

Figure 4: The 95% C.L. upper limit set by CDF on the product of the HV (V is W and Z) production cross section and the branching fraction of $H \to b\bar{b}$ compared to the SM prediction. Also shown is the combined LEP limit.

3 Searches for Higgs Bosons beyond the SM

Among all possible extensions of the SM, Two Higgs Doublet Models (2HDM) [3] are of particular interest, since this structure of the Higgs sector is required in "low-energy" supersymmetric models. The Higgs sector of 2HDM is characterized by eight degrees of freedom. After spontaneous symmetry breaking, three of them become longitudinal polarizations of W and Z bosons, while the remaining five manifest themselves as physical states: two neutral CP-even Higgs bosons, the lighter of which is denoted as h and the heavier as H, one CP-odd Higgs boson, A, and a pair of charged bosons, $H^{\pm}$. At this point one should mention two parameters of 2HDM, which play a crucial role in the Higgs boson phenomenology. These are $\tan\beta$, the ratio of vacuum expectation values of the two Higgs doublets, and α, the mixing angle in the CP-even Higgs sector.

3.1 Flavor Independent Search for $e^+e^- \to hZ$

The distinct feature of 2HDM is the modified couplings of the Higgs bosons to fermions and gauge bosons. Table 1 illustrates the dependence of the neutral Higgs boson couplings to fermions on the parameters α and β in 2HDM of type II, in which one Higgs doublet couples to up-type quarks while the other one to down-type quarks and charged leptons. As one can see, specific choices of parameters

	h	H	A
$u\bar{u}$ (up-type quarks)	$\cos\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cot\beta$
$d\bar{d}$ (down-type quarks)	$\sin\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\tan\beta$
$\ell\ell$ (charged leptons)	$\sin\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\tan\beta$

Table 1: The dependence of fermion couplings to the neutral Higgs bosons on the parameters α and β in 2HDM of type II.

α and β are possible, which lead to the suppression of the Higgs boson couplings to $b\bar{b}$. SM Higgs searches would have a reduced sensitivity in such cases, because of their strong reliance on identification of b-quarks. To investigate these specific scenarios, all four LEP collaborations have performed flavor independent searches for hadronic decays of the Higgs bosons [8]. The preliminary LEP combination of the search results is done for the Higgs-strahlung production mechanism[1] [9]. All decay channels of the Z boson are studied and decays of the Higgs boson into $b\bar{b}$, $c\bar{c}$ and a pair of gluons are considered. None of the LEP collaborations observes an indication of a signal and the search results are translated into the 95% C.L. upper limits on the Higgs-strahlung cross section. This is shown in Figure 5. Assuming SM cross section for the Higgs-strahlung process and the hadronic branching fraction of the Higgs boson equal 1, a lower bound of 112.9 GeV on the Higgs boson mass is obtained at 95% C.L. regardless of the flavor content of the Higgs boson decay products.

[1] Flavor independent searches were also performed for the $e^+e^- \to hA$ production mechanism individually by DELPHI, L3 and OPAL collaborations. However, no LEP combined results of these searches are available yet.

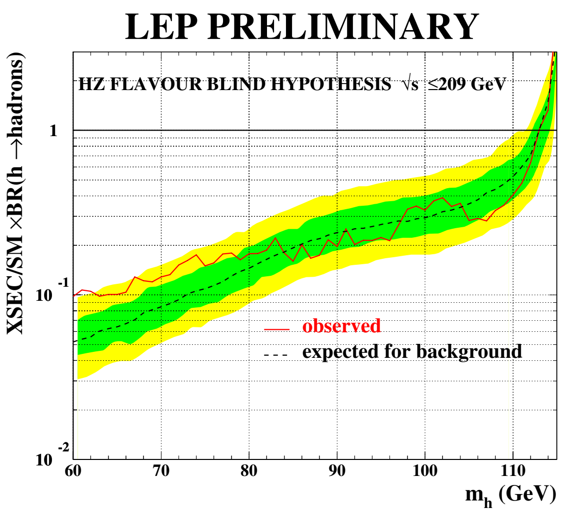

Figure 5: The 95% C.L. upper limit on the Higgs-strahlung cross section, normalized to the value expected in the SM, as a function of the tested Higgs boson mass. The limit is obtained from the LEP combined flavor independent search for the $e^+e^- \to hZ$ process assuming $B(h \to \text{hadrons})$ equal 1. The solid line represents the observed limit, the dashed line stands for the expected limit and the shaded areas show 1σ and 2σ bands centered on the expected limit .

3.2 Searches for Charged Higgs Bosons

At LEP, charged Higgs bosons are expected to be produced in pairs through virtual Z or γ exchange: $e^+e^- \to Z^*/\gamma^* \to H^+H^-$. In 2HDM, the $H^\pm$ mass is not predicted and the tree-level cross-section is fully determined by the mass. The searches are carried out under the assumption that the two decay modes $H^+ \to c\bar{s}$ and $H^+ \to \tau^+\nu$ exhaust the H^+ decay width but the relative branching ratio is regarded as a free parameter. Thus, the searches encompass the following final states: $c\bar{s}\bar{c}s$, $\tau^+\nu\tau^-\bar{\nu}$ and $c\bar{s}\tau^-\bar{\nu} + \bar{c}s\tau^+\nu$. An excess of candidates in the pure hadronic channel in the mass region around 68 GeV is found in the L3 data [10]. However, this effect is not confirmed by other LEP experiments [11]. No signal is found in the pure leptonic and mixed channels. The results from the four collaborations are combined and used to set the 95% C.L. lower limit on the H^+ mass in dependence of the branching fraction $B(H^+ \to \tau^+\nu)$, as shown in Figure 6. A lower limit of 78.6 GeV on the H^+ mass is obtained at 95% C.L. independent of $B(H^+ \to \tau^+\nu)$.

In the SM, the primary decay of the top quark is $t \to W^+b$. The addition of the second Higgs doublet allows the $t \to H^+b$ mode, provided that $m_t > m_{H^+} + m_b$. The dependence of the branching fraction $B(t \to H^+b)$ on $\tan\beta$ is presented in Figure 7 for several representative values of the charged Higgs boson mass. $B(t \to H^+b)$ has a minimum at $\tan\beta = \sqrt{m_t/m_b}$. If $\tan\beta$ differs by about a factor of 10 from $\sqrt{m_t/m_b}$, the branching fraction becomes large, and decreases as m_{H^+} increases. Two different searches for $t \to H^+b$ are performed at Tevatron. An indirect search [12] makes use of the fact that a large branching fraction $B(t \to H^+b)$ suppresses decay rates of $t\bar{t}$ into the $W^+W^-b\bar{b}$ final states. Hence, an observation of a decrease in the $t\bar{t} \to W^+W^-b\bar{b}$ signal expected from the SM would be an indirect indication

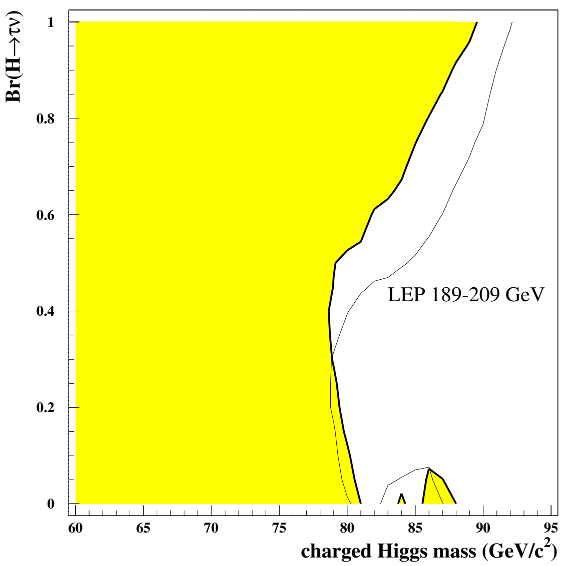

Figure 6: The excluded region in the $(B(H^+ \to \tau^+\nu), m_{H^+})$ plane. Preliminary results from the four LEP collaboration are combined. The shaded area is experimentally excluded at 95% C.L.. The solid line indicates the expected boundary of the excluded region in the absence of a signal.

of the $t \to H^+b$ mode. Direct searches [13] aim to select the $t\bar{t} \to H^+bH^-\bar{b}$ and $t\bar{t} \to H^\pm W^\mp b\bar{b}$ final states, exploiting the $H^+ \to \tau^+\nu$ decay mode. The latter dominates at high $\tan\beta$ values, as shown in Figure 7. The decay mode $H^+ \to c\bar{s}$ is not useful for direct searches due to a large QCD background. Dedicated analyses, performed at Tevatron, assume that there are no top quark decays other than $t \to W^+b$ and $t \to H^+b$. No signal is found and the results are used to constrain parameters of 2HDM. As an example, Figure 8 presents D0 results, expressed in terms of the 95% C.L. excluded regions in the $(m_{H^+}, \tan\beta)$ plane.

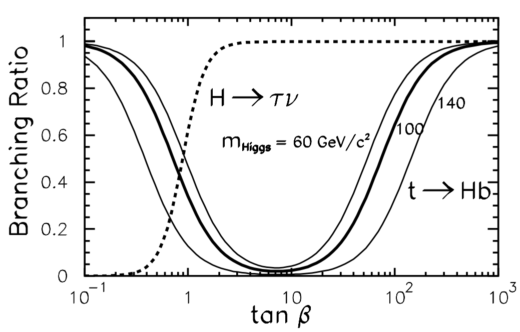

Figure 7: Branching fractions $B(t \to H^+b)$ and $B(H^+ \to \tau^+\nu)$ as a function of $\tan\beta$.

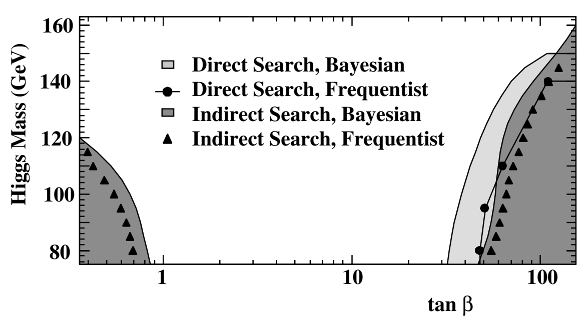

Figure 8: The 95% C.L. excluded regions in the $(m_{H^+}, \tan\beta)$ plane for the top quark mass $m_t = 175$ GeV and $\sigma(p\bar{p} \to t\bar{t}) = 5.5$ pb. Results are obtained by the D0 collaboration.

3.3 Searches for the Neutral Higgs Bosons of the MSSM

Supersymmetry is a tempting theoretical concept which provides an elegant solution of the so-called "hierarchy" problem and incorporates gravity in a consistent way into the model [15]. The Higgs sector of the Minimal Supersymmetric extension of the Standard Model (MSSM) [16] corresponds to the 2HDM of type II and hence contains the five physical states indicated above.

At LEP, searches for the neutral Higgs bosons of the MSSM are performed, exploiting two production mechanisms: the Higgs-strahlung and associated Higgs boson pair production, $e^+e^- \to Z^* \to hA$. For the Higgs-strahlung process, the same event topologies as in the SM Higgs search are studied. For the hA production, the final states studied are: $hA \to b\bar{b}b\bar{b}$ and $hA \to b\bar{b}\tau^+\tau^-, \tau^+\tau^- b\bar{b}$. To improve search sensitivity in the MSSM parameter regions where the decay $h \to AA$ opens, some collaborations have searched also for the $e^+e^- \to hZ \to AAZ$ process [17]. No evidence for the production of the neutral MSSM Higgs bosons is found in the LEP combined data [18]. Hence, the search results are interpreted in terms of exclusion of the MSSM parameter regions. Figure 9 shows the 95% C.L. excluded regions in the $(\tan\beta, m_h)$ plane for the so-called "$m_h - \max$" scenario, which yields the maximal theoretical upper limit on m_h in the model. In this scenario, the LEP combined data establish the 95% C.L. lower limits on the h and A boson masses of 91.0 GeV and 91.9 GeV, respectively.

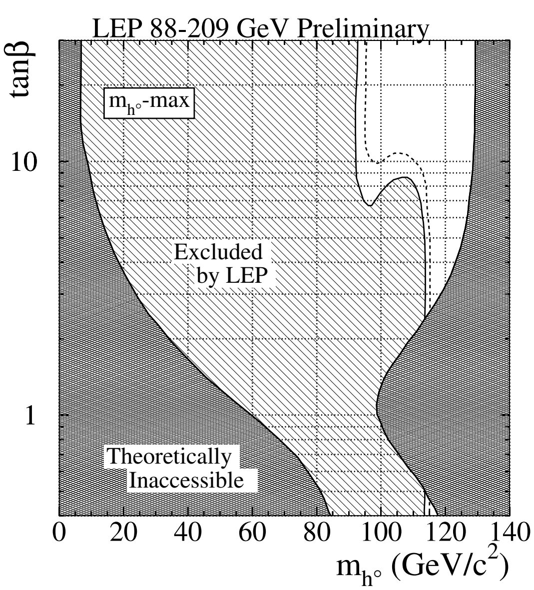

Figure 9: The 95 % C.L. exclusion contours in the $(\tan\beta, m_h)$ projection for the "$m_h - \max$" scenario. The results of the four LEP experiments are combined. The hatched area is excluded, the filled area is theoretically inaccessible and the dashed line indicates the expected boundary of the excluded region in the absence of a signal.

Using RunI data, the CDF collaboration has carried out the search for the neutral supersymmetric Higgs bosons in the process $p\bar{p} \rightarrow b\bar{b}\phi \rightarrow b\bar{b}b\bar{b}$ with $\phi = \mathrm{h}, \mathrm{H}$ and A, exploiting the enhanced Higgs-bottom Yukawa coupling at high values of $\tan\beta$ [19]. A dedicated analysis is elaborated to select events with four or more jets of which at least three being tagged as b jets. The study of dijet invariant mass spectra in the selected sample revealed no evidence for a signal. Shown in Figure 10 are the exclusion contours in the $(\tan\beta, m_h)$ plane for the two representative scenarios of the scalar top mixing.

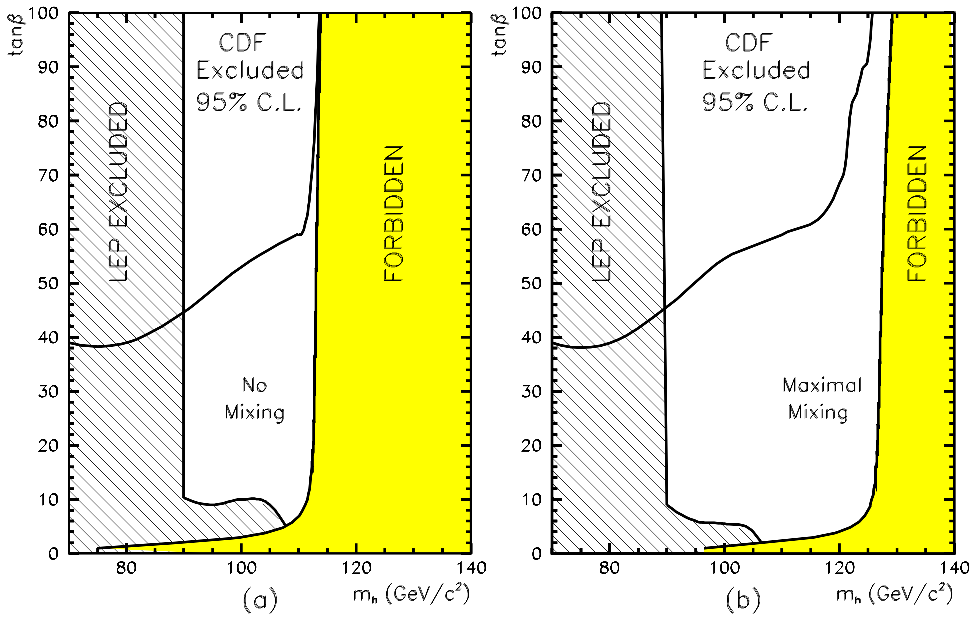

Figure 10: The 95% C.L. excluded regions in the $(\tan\beta, m_h)$ plane for the two scalar top mixing scenarios : a) "no mixing", b) "maximal mixing". Results are obtained by the CDF collaboration. The LEP excluded regions shown here are obsolete.

4 Conclusions

Searches for Higgs bosons of various theoretical models are performed at LEP and Tevatron. No strong indication of the production of Higgs bosons is found. Negative results of the searches are used to constrain parameters in the Higgs sector of the SM and its various extensions. In the SM, the 95% C.L. lower limit of 114.4 GeV on the Higgs boson mass is obtained from the direct searches at LEP.

Searches for Higgs bosons will be one of the main objectives during the RunII data taking period at Tevatron. Higgs searches will be also continued at the Large Hadron Collider (LHC) at CERN. If the Higgs boson is found, its profile will be explored at a future linear e^+e^- collider. The physics results from these experimental facilities are anticipated to shed a light on the problem of electroweak symmetry breaking and give an insight into the origin of mass.

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