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Neutral Higgs bosons in the standard model and in the minimal supersymmetric model: Searches at LEP

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Abstract. During the twelve years of operation of the e^+e^- collider LEP, the associated collaborations, ALEPH, DELPHI, L3 and OPAL, have extensively searched for Higgs bosons over a broad range of masses. We present the final results from LEP for the standard model Higgs boson which are obtained from a statistical combination of the data from the four experiments. We also present preliminary combined results for neutral Higgs bosons in the minimal supersymmetric model (MSSM) where the Higgs sector is assumed to be CP invariant. Finally, we discuss an alternative MSSM scenario including CP violation in the Higgs sector.

Keywords. Higgs bosons; standard model; minimal supersymmetric model; searches at LEP.

1. Introduction

One of the challenges in high-energy particle physics is the discovery of Higgs bosons. Their existence is related to the spontaneous breaking of electroweak symmetry and to the generation of elementary particle masses.

The standard model (SM) predicts a single neutral Higgs boson H^0. Although the mass of H^0 is a free parameter, self-consistency of the theory requires that mass to be less than about 1 TeV [1]. Indirect experimental bounds are obtained from fits to electroweak observables in Z boson decays and to the masses of the top quark and the $W^\pm$ boson, which are all sensitive to the Higgs mass through radiative corrections. The upper bound from these fits is 193 GeV/c^2 (95% CL) [2]. Direct searches for the SM Higgs boson have been performed by all four LEP experiments. Their final results [3–6] have been statistically combined to increase the overall sensitivity of the LEP data [7].

Beyond the SM, supersymmetric (SUSY) models are of interest since they provide a coherent framework for grand unification and a possible explanation for the 'scale hierarchy problem'. The minimal supersymmetric model (MSSM) predicts three neutral Higgs bosons and a pair of charged Higgs bosons. At least one of the neutral Higgs bosons should have its mass at the electroweak energy scale ($\lesssim$ 130 GeV/c^2). Most searches have assumed thus far that the Higgs interactions are CP invariant. A CP violating scenario has recently been proposed as a possible model for the cosmic baryon asymmetry [8] and this scenario has been examined by the OPAL Collaboration [9].

2. Searches for the standard model Higgs boson

At LEP, the SM Higgs boson is expected to be produced mainly through the Higgsstrahlung process $e^+e^- \to H^0Z^0$ and to decay predominantly into $b\bar{b}$ quark pairs. The final states sought at LEP encompass the four-jet channel $(H^0 \to b\bar{b})(Z^0 \to q\bar{q})$, the missing energy channel $(H^0 \to b\bar{b})(Z^0 \to \nu\bar{\nu})$, the leptonic channels $(H^0 \to b\bar{b})(Z^0 \to \ell^+\ell^-)$ with $\ell = e$ or μ, and the tau channels $(H^0 \to b\bar{b})(Z^0 \to \tau^+\tau^-)$ and $(H^0 \to \tau^+\tau^-)(Z^0 \to q\bar{q})$.

The LEP collider, operating first at c.m. energies close to M_Z, definitively excluded H^0 masses between zero and about 65 GeV. Later the energy was increased, reaching $\sqrt{s} = 209$ GeV shortly before the final shutdown in November 2000. The sensitive range could thereby be extended to about 120 GeV/c^2. In the data sets collected at the highest energies, ALEPH observed [3] an excess of events consistent with a SM Higgs boson with about 115 GeV/c^2 mass. The other experiments [4–6] reported no significant deviation from the background.

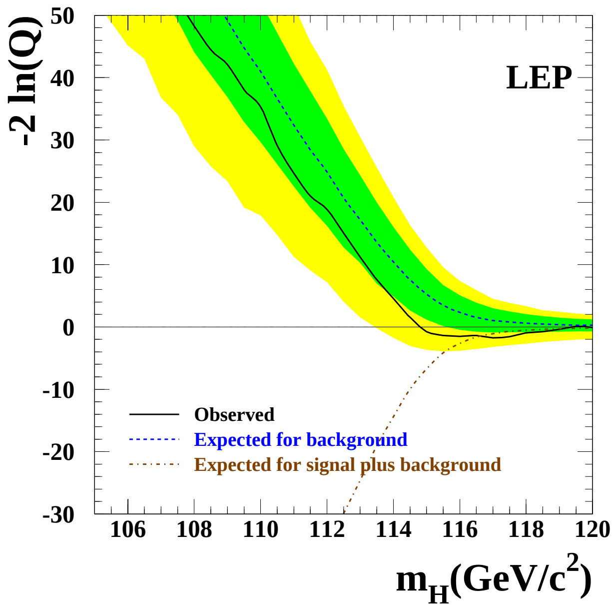

Figure 1. Observed and expected behaviour of the test statistic $-2\ln Q$ as a function of the test mass m_{H^0}, obtained by combining the data of the four LEP experiments. The full curve represents the observation; the dashed curve shows the median background expectation; the dark and light shaded bands represent the 68% and 95% probability bands about the median background expectation. The dash-dotted curve indicates the position of the minimum of the median expectation for the signal plus background hypothesis when the signal mass given on the abscissa is tested.

The search sensitivity has been increased by combining statistically the data of the four experiments [7]. The combined LEP data were examined in a likelihood test for their consistency with the background (b) hypothesis and the signal plus background ($s+b$) hypothesis. The ratio of the likelihoods $Q = \mathcal{L}_{s+b}/\mathcal{L}_b$ was taken as test statistic (for convenience, the logarithmic form $-2\ln Q$ was used). Figure 1 shows $-2\ln Q$ for the LEP data combined. There is a shallow minimum in the observed curve starting at about 115 GeV/c^2 mass. The negative values in this range indicate that the $s+b$ hypothesis is favoured over the b hypothesis, albeit at low significance.

The confidence of this observation has been evaluated by calculating the p-values [10] for the two hypotheses. These are obtained by integrating the corresponding PDFs which come from detailed Monte Carlo simulations. At a test mass of 115 GeV/c^2 where ALEPH reported an excess, the p-value of the LEP data for the background hypothesis is 0.09 while that for the signal plus background hypothesis is 0.15. As a main result, a 95% CL lower bound of 114.1 GeV/c^2 is set by LEP on the mass of the SM Higgs boson.

3. Neutral MSSM Higgs bosons: The CP conserving scenario

Assuming CP invariance, the spectrum of neutral MSSM Higgs bosons consists of two CP-even scalars h^0 and H^0 and a CP-odd scalar A^0 (see, e.g., [11]). The mass of the light CP-even scalar h^0 is predicted to be at the electroweak energy scale. At tree level, two parameters are required to fix all Higgs boson masses and couplings; a convenient choice is $\tan\beta = v_2/v_1$ (the VEV ratio of the two MSSM Higgs fields) and m_{A^0}, the mass of the CP-odd scalar. Radiative corrections introduce a number of soft SUSY breaking parameters which may strongly modify the masses and couplings [12], but the mass of h^0 is still expected to be less than about 130 GeV/c^2. At LEP, the main production processes are $e^+e^- \to h^0 Z^0$ and $e^+e^- \to h^0 A^0$ which are complementary in their cross-sections. The decay properties of h^0 and A^0 are similar to those of the SM Higgs boson, with a strong $b\bar{b}$ component.

The searches at LEP for h^0 and A^0 bosons are carried out in a constrained MSSM where universal masses $M_{\rm SUSY}$ and M_2 are assumed for sfermions and gauginos at the electroweak scale. Besides the main parameters $\tan\beta$ and m_{A^0}, the Higgs sector is further influenced by the Higgs mixing parameter μ and the trilinear coupling A. The gluino mass $m_{\tilde{g}}$, which affects the results via stop and sbottom loops, is fixed to 800 GeV, and the top quark mass is set to 174.3 GeV.

These searches are interpreted in 'benchmark' scenarios [13] where some of the above parameters are fixed: $M_{\rm SUSY} = 1$ TeV, $M_2 = 200$ GeV and $\mu = -200$ GeV. Furthermore, in the *no-mixing* scenario the stop mixing is set to zero by choosing $X_t \equiv A - \mu\cot\beta = 0$. The m_{h^0}-max scenario is designed to maximise m_{h^0} by choosing $X_t = 2M_{\rm SUSY}$; this scenario yields conservative limits, in particular for $\tan\beta$.

The preliminary MSSM limits which are obtained from combining the LEP data [14] are shown in figure 2 for the m_{h^0}-max scenario. The excluded regions are presented here in the (m_{h^0}, $\tan\beta$) projection. The 95% CL mass bounds are

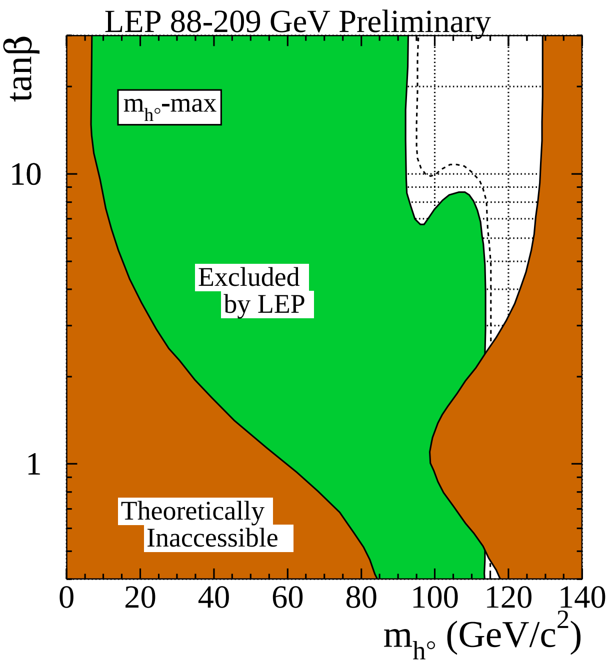

Figure 2. The 95% CL bounds on m_{h^0} and $\tan\beta$ from LEP in the m_{h^0}-max benchmark scenario. The shaded areas are excluded either by the model or by the experiments.

$m_{h^0} > 91.0$ GeV/c^2 and $m_{A^0} > 91.9$ GeV/c^2. Values of $\tan\beta$ from 0.5 to 2.4 are excluded; however, this exclusion may become weaker if, for example, the top mass is higher than the assumed value. The no-mixing scenario is almost entirely excluded (see [14]).

4. The CP violating MSSM scenario

CP violation can be introduced in the MSSM Higgs sector, for example, by first-order loop corrections from third generation squarks to the otherwise CP invariant Higgs potential. In such a scenario [8] the three neutral Higgs bosons, H_i ($i = 1, 2, 3$) are mixtures of the CP-even and CP-odd Higgs fields. As in the CP invariant scenario, the lightest Higgs boson H_1 is expected at the electroweak energy scale; however, for particular choices of the model parameters, the H_1 boson may decouple partially or completely from the Z boson. Moreover, H_2 and H_3 may be too heavy to be produced at LEP. For these reasons, the searches are experimentally more challenging in such a scenario, and large domains of the parameter space which are excluded in CP conserving scenarios may still be open in models with CP violation.

The neutral Higgs bosons are expected to be produced both by the Higgsstrahlung process $e^+e^- \to H_i Z$ and the pair production process $e^+e^- \to H_i H_j$ ($i \neq j$) [8]. The cross-sections are complementary but the sum rules are more complex than in the

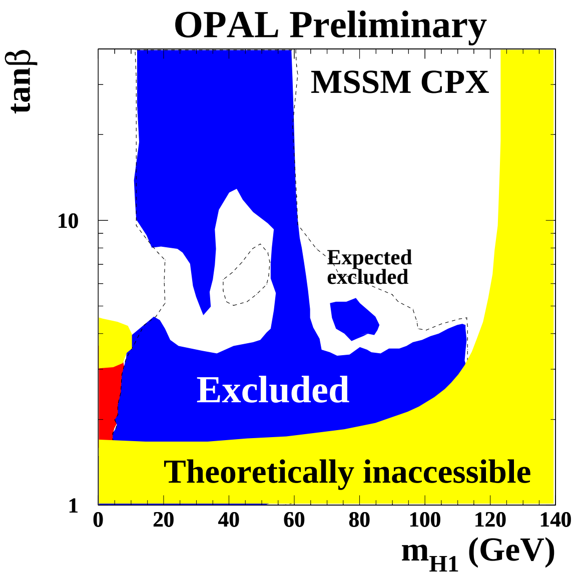

Figure 3. The 95% CL bounds on m_{H_1} and $\tan\beta$ in the CPX MSSM scenario from a preliminary OPAL analysis. The shaded areas are excluded either by the model or by the experiment. The areas delimited by the dashed lines are expected to be excluded on the basis of the Monte Carlo simulation.

CP conserving case and depend on the parameter choices. The decay properties are similar to those in the CP conserving case, with Higgs bosons decaying predominantly into $b\bar{b}$ pairs.

The OPAL search [9] is performed in the CPX benchmark scenario [15] where the parameters are chosen in such a way as to maximise the phenomenological differences with respect to the CP conserving scenario. This is obtained typically for small M_{SUSY} and large values of μ and when the CP violating phases are maximal. Figure 3 shows the preliminary OPAL exclusions in the $(m_{H_1}, \tan\beta)$ plane. Values of $\tan\beta$ less than 3.2 are excluded at 95% CL but there is no absolute limit on the mass of H_1. There are large unexcluded regions at $\tan\beta$ between 4 and 10 where the decoupling of H_1 from the Z boson is particularly important and the signal is spread out over a number of weak decay channels. The unexcluded domains become even stronger if the top quark mass turns out to be larger than the assumed value of 174.3 GeV/c^2 [9].

References

[1] N Cabibbo *et al*, *Nucl. Phys.* **B158**, 295 (1979)
[2] ALEPH, DELPHI, L3, OPAL, The LEP electroweak working group, CERN-EP/2002-091; hep-ex/0212036
[3] ALEPH Collaboration: R Barate *et al*, *Phys. Lett.* **B526**, 191 (2002)
[4] DELPHI Collaboration: J Abdallah *et al*, CERN-EP/2003-008, hep-ex/0303013; submitted to *Euro. Phys. J. C*

[5] L3 Collaboration: M Acciarri *et al*, *Phys. Lett.* **B517**, 319 (2001)
[6] OPAL Collaboration: G Abbiendi *et al*, CERN-EP/2002-059, hep-ex/0209078; to be published in *Euro. Phys. J. C*
[7] ALEPH, DELPHI, L3, OPAL, the LEP Higgs working group, *Search for the standard model Higgs boson at LEP*, CERN-EP/2003-011, submitted to *Phys. Lett. B*
[8] A Pilaftsis, *Phys. Rev.* **D58**, 096010 (1998); *Phys. Lett.* **B435**, 88 (1998)
G L Kane and L-T Wang, *Phys. Lett.* **B488**, 383 (2000)
[9] OPAL Physics Note PN517 (March 2003)
[10] K Hagiwara *et al*, *Phys. Rev.* **D66**, 010001-1 (2002), Rev. No. 31 on *Statistics*, p. 229
[11] H E Haber and G Kane, *Phys. Rep.* **C117**, 75 (1985)
[12] J Ellis, G Ridolfi and F Zwirner, *Phys. Lett.* B257, 83 (1991)
M Carena, M Quiros and C E M Wagner, *Nucl. Phys.* **B461**, 407 (1996)
S Heinemeyer, W Hollik and G Weiglein, *Phys. Lett.* **B455**, 179 (1999)
J R Espinosa and R J Zhang, *J. High Energy Phys.* **0003**, 026 (2000); hep-ph/9912236
[13] M Carena, S Heinemeyer, C E M Wagner and G Weiglein, hep-ph/9912223
[14] ALEPH, DELPHI, L3, OPAL, LEP Higgs working group
LHWG Note/2001-04, hep-ex/0107030, (and refs to the individual experiments)
[15] M Carena *et al*, *Nucl. Phys.* **B599**, 158 (2001)