Search for Higgs in the Two Doublet Models

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Two Higgs Doublet Models are attractive extensions of the Standard Model. The most recent results obtained by the LEP collaborations on searches for Higgs bosons in the context of Two Higgs Doublet Models are presented.

1. Introduction

In the minimal Standard Model (SM) the Higgs sector comprises only one complex Higgs doublet [1] resulting in one physical neutral Higgs scalar whose mass is a free parameter of the theory. However, it is important to study extended models containing more than one physical Higgs boson in the spectrum. In particular, Two Higgs Doublet Models (2HDMs) are attractive extensions of the SM since they add new phenomena with the fewest new parameters; they satisfy the constraints of $\rho \approx 1$ and the absence of tree-level flavour changing neutral currents. In the context of 2HDMs the Higgs sector comprises five physical Higgs bosons: two neutral CP-even scalars, h^0 and H^0 (with $m_{\mathrm{h}} < m_{\mathrm{H}}$), one CP-odd scalar, A^0, and two charged scalars, $\mathrm{H}^{\pm}$. The couplings between the Higgs bosons and the fermions determine the type of the model considered. In the Type II model the first Higgs doublet (ϕ_1) couples only to down–type fermions and the second Higgs doublet (ϕ_2) couples only to up–type fermions. In the Type I model the quarks and leptons do not couple to the first Higgs doublet (ϕ_1), but couple to the second Higgs doublet (ϕ_2). The minimal supersymmetric extension of the SM [2] is a Type II 2HDM, in which the introduction of supersymmetry adds new particles and constrains the parameter space of the Higgs sector of the model. Therefore 2HDMs of type II (2HDM(II)) are more general than the MSSM. 2HDM(II) have 6 free parameters:

- the four Higgs masses, namely, m_{A}, m_{h}, m_{H}, $m_{\mathrm{H}^{\pm}}$;
- the angle β ($0 \leq \beta \leq \pi/2$), where $\tan\beta = v_2/v_1$ is defined as the ratio of the vacuum expectation values of the two scalar fields.
- the angle α defined as the mixing angle that relates the physical mass eigenstates with the field doublets. The most general 2HDM(II) is studied by varying the α angle in a π lenght range.

At the centre-of-mass energies accessed by LEP, the h^0 and A^0 bosons are expected to be produced predominantly via two processes: the *Higgs–strahlung* process $\mathrm{e}^+\mathrm{e}^- \to \mathrm{h}^0\mathrm{Z}^0$ and the *pair–production* process $\mathrm{e}^+\mathrm{e}^- \to \mathrm{h}^0\mathrm{A}^0$. The cross-sections for these two processes, σ_{hZ} and σ_{hA}, are related at tree-level to the SM cross-sections through the following relations [2]:

$$\mathrm{e}^+\mathrm{e}^- \to \mathrm{h}^0\mathrm{Z}^0 : \quad \sigma_{\mathrm{hZ}} = \sin^2(\beta-\alpha)\ \sigma^{\mathrm{SM}}_{\mathrm{HZ}}, \quad (1)$$

$$\mathrm{e}^+\mathrm{e}^- \to \mathrm{h}^0\mathrm{A}^0 : \quad \sigma_{\mathrm{hA}} = \cos^2(\beta-\alpha)\ \bar{\lambda}\ \sigma^{\mathrm{SM}}_{\mathrm{HZ}}, \quad (2)$$

where $\sigma^{\mathrm{SM}}_{\mathrm{HZ}}$ is the Higgs–strahlung cross-section for the SM process $\mathrm{e}^+\mathrm{e}^- \to \mathrm{H}^0_{\mathrm{SM}}\mathrm{Z}^0$, and $\bar{\lambda}$ is a phase–space factor.

The coefficients $\sin^2(\beta-\alpha)$ and $\cos^2(\beta-\alpha)$ which appear in Eqs. (1) and (2) determine the production cross-sections. The decay branching ratios to the various final states are also determined by α and β. In the 2HDM(II) the tree-level couplings of the h^0 and A^0 bosons to the up– and down–type quarks relative to the canonical SM values are [2]:

$$\mathrm{h}^0\mathrm{b}\overline{\mathrm{b}} : -\frac{\sin\alpha}{\cos\beta}, \quad \mathrm{A}^0\mathrm{b}\overline{\mathrm{b}} : \ \tan\beta,$$

$$\mathrm{h}^0\mathrm{c}\overline{\mathrm{c}} : \frac{\cos\alpha}{\sin\beta}, \quad \mathrm{A}^0\mathrm{c}\overline{\mathrm{c}} : \ \cot\beta, \quad (3)$$

indicating the need for a scan over both angles when considering the different production cross-section mechanisms and final state topologies.

2. Scan of the Neutral sector of 2HDM(II)

A detailed scan of the Neutral sector of the 2HDM(II) has been performed by the OPAL collaboration [3]. Each of the scanned points is considered as an independent scenario within the 2HDM(II), and results are provided for each point in the ($m_{\rm h}$, $m_{\rm A}$, tanβ, α) space. The masses $m_{\rm h}$ and $m_{\rm A}$ are varied such that the kinematically accessible range at LEP is fully covered: $1 \leq m_{\rm h} \leq 120$ GeV, 3 GeV $\leq m_{\rm A} \leq 2.0$ TeV. The choice $0 \leq \beta \leq \pi/2$ derives from $v_1, v_2 > 0$. Five values of α ($\alpha = \pi/2$, $\pi/4$, 0, $-\pi/4$, and $-\pi/2$) have been chosen in the range $-\pi/2 \leq \alpha \leq \pi/2$: they extend the analysis to the particular cases of maximal and minimal mixing in the neutral CP-even sector of the 2HDM(II) ($\alpha = \pm\pi/4$ and $\pm\pi/2$, respectively). Searches for Neutral Higgs bosons performed at OPAL at $\sqrt{s} = m_{\rm Z}$ and for $189 \leq \sqrt{s} \leq 209$ GeV have been interpreted in the context of the 2HDM(II), i.e., searches for $\rm h^0$ production via the Higgs–strahlung process and for $\rm h^0$ and $\rm A^0$ via the pair–production process. All final state topologies with the $\rm Z^0$ decaying into pairs of quarks and leptons and the $\rm h^0$ and $\rm A^0$ decaying into $\rm b\bar{b}$ are taken into account. The decay of $\rm h^0$ into $\rm A^0A^0$, that is dominant when kinematically allowed, has also been considered. Higgs bosons couple to fermions with a strength proportional to the fermion masses, favouring the decays into pairs of b–quarks and tau leptons at LEP energies. However, with values of α and tanβ close to zero the decays into up–type light quarks and gluons through quark loops become dominant, motivating the development and inclusion in this study of analyses of the final states with $\rm h^0$ and $\rm A^0$ decaying into $\rm q\bar{q}$ pairs, so called *flavour independent*. The limit on non-standard contributions to the invisible width, $\Delta\Gamma_{inv} < 2$ MeV at 95 % Confidence Level (C.L.) extracted from the latest LEP combined $\rm Z^0$ lineshape results [4] is used to set upper limits on the cross-section of $\rm Z^0$ decays into final states with $\rm h^0$ and $\rm A^0$ bosons. In Figure 1 the excluded regions in the ($m_{\rm h}$, $m_{\rm A}$) plane independent of α are given together with the calculated expected exclusion limits. A particular ($m_{\rm h}$, $m_{\rm A}$) point is excluded at 95% C.L. if it is excluded for all scanned values of tanβ and α. Different domains of tanβ are shown: $0.4 \leq$ tan$\beta \leq 58.0$ (darker grey area) and two restricted ranges, i.e., $0.4 \leq$ tan$\beta \leq 1.0$ (lighter grey area) and $1.0 <$ tan$\beta \leq 58.0$ (hatched area), for which enlarged excluded regions are obtained. A rectangular region $1 \leq m_{\rm h} \leq 58$ GeV for $10 \leq m_{\rm A} \leq$ 65 GeV is fully excluded at 95% C.L. independent of α and tanβ. The cross–hatched region shows the exclusion provided by the constraints on the width of the $\rm Z^0$ common to all the scanned values of α and tanβ.

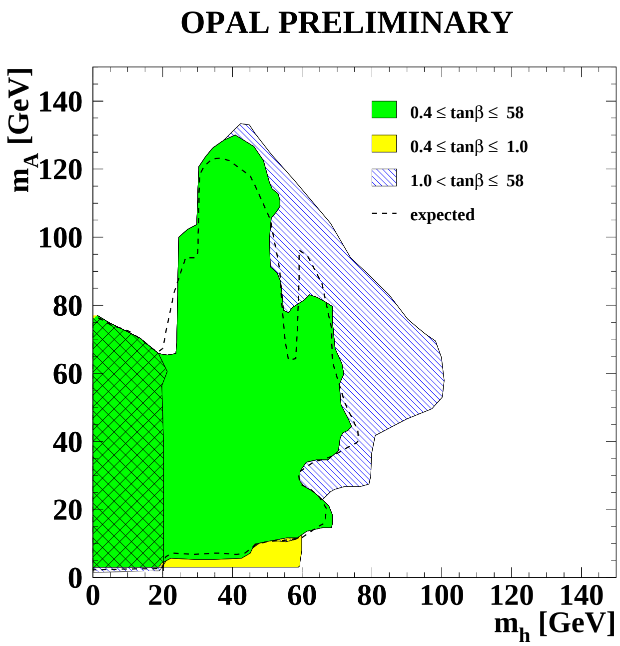

Figure 1. *Excluded ($m_{\rm h}$, $m_{\rm A}$) region independent of α, together with the expected exclusion limit. The cross–hatched region is excluded using constraints from $\Gamma_{\rm Z}$ only. Expected exclusion limits are shown as a dashed line.*

The DELPHI collaboration has also studied the 2HDM(II) parameter space [5]. The following final states have been analysed at $\sqrt{s}$ = 189-208 GeV:

1. $e^+e^- \rightarrow h^0A^0 \rightarrow 4b$,
2. $e^+e^- \rightarrow h^0A^0 \rightarrow A^0A^0A^0 \rightarrow b\bar{b}b\bar{b}b\bar{b}$,
3. $e^+e^- \rightarrow Z^0h^0 \rightarrow Z^0A^0A^0 \rightarrow q\bar{q}b\bar{b}b\bar{b}$,
4. $e^+e^- \rightarrow A^0h^0 \rightarrow h^0Z^0h^0 \rightarrow b\bar{b}b\bar{b}q\bar{q}$.

For channel number 1. also 1994-1995 data ($\sqrt{s} \approx m_Z$) have been analysed.
For each process a global suppression factor is defined as the product of cross-section times branching ratio suppression in the 2HDM(II) with respect to the SM. Such a procedure allows a model independent approach: to see whether a given point in any specific model parameter space is excluded it is sufficient to calculate the corresponding global suppression factor and to compare it with the excluded value. This study is specifically searching for decays of the h^0 and A^0 into b–quarks and therefore no exclusion can be obtained in the most general 2HDM(II) in the parameter space regions where the h^0 or $A^0$are not decaying to $b\bar{b}$. Figure 2 shows the countours of suppression factor excluded at 95% C.L. in the (m_h,m_A) plane by the 4b final state analysis (channel 1.).

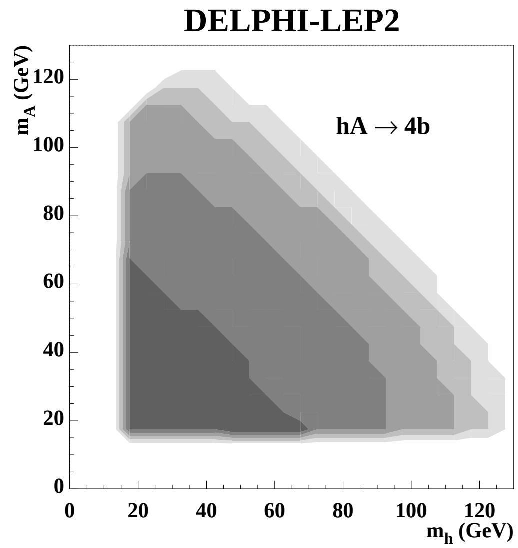

Figure 2. *Region in the (m_h,m_A) plane where pair–production of h^0A^0 and decay into four b–quarks is excluded by the present analysis. The levels of gray correspond to suppression factors of 0.1, 0.3, 0.5, 0.75, and 1, from darker to lighter gray, respectively.*

3. Study of Yukawa production mechanism

Another important process for Higgs production in addition to the Higgs-strahlung and pair-production is the Yukawa process shown in Figure 3. For a sufficiently small $\sin^2(\beta - \alpha)$, the h^0 produced through the Higgs-strahlung process can not be seen in the data collected at LEP due to the cross-section suppression factor. Under the assumption that the Higgs-strahlung process is suppressed and pair-production is kinematically forbidden, $m_A + m_h > \sqrt{s}$, the Yukawa process becomes the dominant process for Higgs production at LEP. This scenario can easily be realised in the general 2HDM since its parameters are not constrained theoretically [6,7].

The cross-section of the Yukawa process [8]

$$\sigma_{\rm Yukawa} \propto m_f^2\, N_c\, \xi_f^2 \qquad (4)$$

is proportional to the squared fermion mass, m_f^2, the colour factor, N_c, of the emitting fermion, and an enhancement factor ξ_f^2, which describes the coupling between the Higgs boson and the emitting fermion (see equation 3). The range of ξ_d and ξ_u, i.e., the coupling to down- and up-type quarks and leptons for which a detectable signal would be produced, can be divided into two cases: (i) $\xi_u \gg 1$ and (ii) $\xi_d \gg 1$, i.e., enhancement of the up-type and down-quark and leptons coupling to the Higgs, respectively. However, an enhancement of the up-type quarks coupling, sufficient from the production and detection point of view, is already excluded by a search for $Z^0 \rightarrow h^0(A^0)\gamma$ process [9]. Searches have been performed by the LEP experiments in the four final states : $2b2\tau, 4b, 2\tau 2b$ and 4τ [10–12]. Only data collected at $\sqrt{s} \approx m_Z$ (LEP1) were analysed since, although the luminosity collected at $130 \leq \sqrt{s} \leq 209$ GeV (LEP2) is a factor five higher than the luminosity at the Z peak, the number of produced b-quarks is 100 times smaller. The DELPHI and OPAL collaborations produced the most recent results performing an analysis in the final state with 4 b-quarks on 1994-1995 LEP1 data

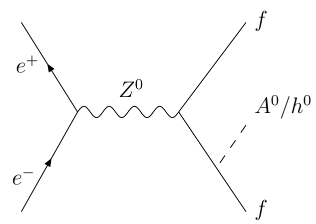

Figure 3. *The Born level Yukawa production process Feynmann diagram.*

[13] and with 2 b-quarks and 2τ on 113.1 pb^{-1} of LEP1 data [14], respectively. Figure 4 shows the 95% C.L. exclusion within 2HDM(II) in the DELPHI 4b channel. The results are greatly improved with respect to the previous analysis [11] that was based on a reinterpretation of the DELPHI measurement of the gluon splitting into $\mathrm{b\bar{b}}$.

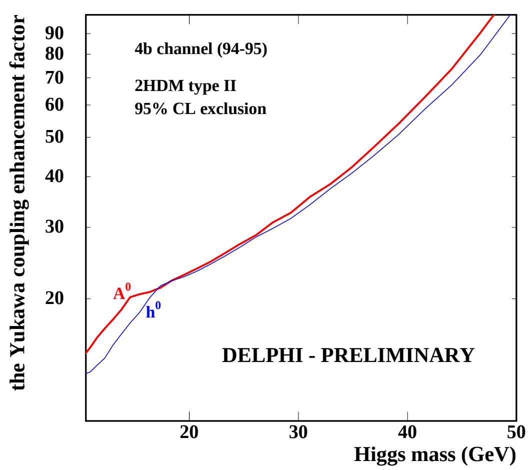

Figure 4. *The exclusion within the 2HDM(II) in the 4b channel. The enhancement factor shown on the vertical axis corresponds to* $\tan\beta$ *and* $\sin\alpha/\cos\beta$ *for* A^0 *and* h^0*, respectively.*

Recent measurements of the anomalous magnetic moment of the muon, $a_\mu = \frac{1}{2}(g-2)_\mu$, have given a result which deviates from the Standard Model expectation by ≈ 2.6 standard deviations [15]. Depending on the estimation of the hadronic contribution to the muon anomalous magnetic moment, the 90% C.L. ranges for the contribution of New Physics $\delta a_\mu(\mathrm{NP})$ to the muon anomalous magnetic moment vary in the range $112\times10^{-11} \leq \delta a_\mu(\mathrm{NP}) \leq 690\times10^{-11}$ [16–18].

Light Higgs bosons A^0 and h^0 could contribute to a_μ via loop diagrams. A one-loop calculation [19] predicts positive contributions $\delta a_\mu^I(\mathrm{h}) > 0$ for the h^0, and negative contributions $\delta a_\mu^I(\mathrm{A}) < 0$ for the A^0. The two-loop contributions, due to the stronger coupling of the Higgs fields to loops with heavy quarks, turn out to be larger in magnitude than the one-loop terms, and of opposite sign [20], giving a total positive contribution $\delta a_\mu^{II}(\mathrm{A}) > 0$ for the A^0. However, the two-loop terms gives a total negative contribution $\delta a_\mu^{II}(\mathrm{h}) < 0$ for the h^0, thus suggesting that the h^0 can not account for the BNL observation. The 95% C.L. limits derived within the 2HDM model by the OPAL $2b2\tau$ analysis [14] are shown in Figure 5 (a) and (b) for CP-odd and CP-even Higgs production, respectively. In the $\mathrm{h}^0$and A^0mass range from 9.4 GeV to 11.0 GeV the effect of the mixing of the Higgs bosons with $\mathrm{b\bar{b}}$ bound states has been taken into account in the calculation of the h^0 and A^0 branching ratios.

Figure 5 (a) and (b) also show the ISO-lines of the contribution from the two-loop and earlier one-loop calculations, respectively. The OPAL data exclude positive contributions $\delta a_\mu^I(\mathrm{h}) > 100\times10^{-11}$ for h^0 masses between 4.0 and 10.7 GeV at the one-loop level, and $\delta a_\mu^{II}(\mathrm{A}) > 100\times10^{-11}$ for A^0 masses between 4.0 and 9.9 GeV at the two-loop level. Similar limits have been derived from radiative Υ decays [21,22] for $\mathrm{h}^0/\mathrm{A}^0$ masses lighter than about 8 GeV with, however, large QCD uncertainties.

4. The charged Higgs sector

Charged Higgs bosons are predicted by 2HDMs. At LEP2 energies charged Higgs bosons are expected to be produced mainly through the process $\mathrm{e^+e^-}\rightarrow\mathrm{H^+H^-}$. In the MSSM, at tree-level, the $\mathrm{H}^\pm$ is constrained to be heavier than the $\mathrm{W}^\pm$ bosons, but for specific choices of the parameters, loop corrections can bring the mass

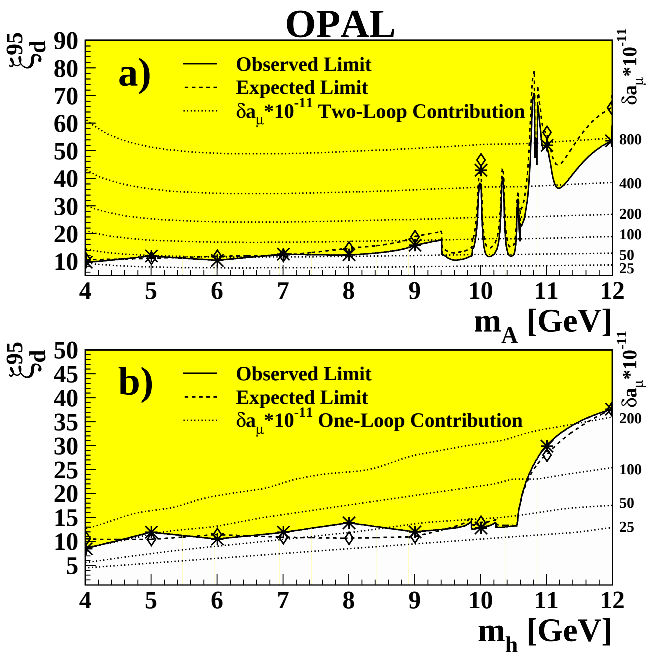

Figure 5. *Expected and Observed excluded values of ξ_d at 95% C.L. in the 2HDM(II) with Standard Model particle content for the Yukawa production of* A^0 *(upper plot) and for the* h^0 *(lower plot) with the mixing to* $\mathrm{b\bar{b}}$ *bound states taken into account. The dotted lines are the contours of the predicted Higgs contribution at one-loop and two-loop for* h^0 *and* A^0*, respectively, to the muon anomalous magnetic moment, δa_μ(Higgs).*

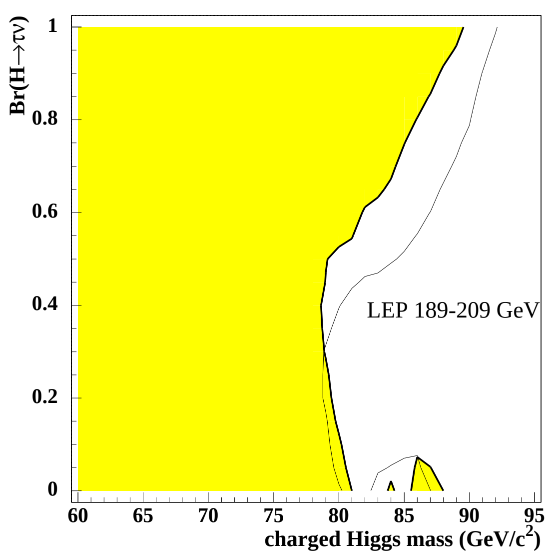

Figure 6. *The 95% C.L. bounds on $m_{\mathrm{H}^\pm}$ as a function of the branching ratio B($\mathrm{H}^+ \to \tau^+\nu$), combining the data collected by the four LEP experiments at energies from 189 to 209 GeV. The expected exclusion limits are indicated by the thin solid line and the observed limits by the thick solid one. The shaded area is excluded at the 95% C.L.*

to lower values. Thus, any signal for $\mathrm{H}^+\mathrm{H}^-$ would indicate either new physics beyond the MSSM or a rather extreme set of MSSM parameter values. In 2HDMs the $\mathrm{H}^\pm$ mass is not constrained, and the tree-level cross-section is fully determined by the mass [24]. The searches are carried out under the assumption that the two decays $\mathrm{H}^+ \to \mathrm{c\bar{s}}$ and $\mathrm{H}^+ \to \tau^+\nu$ exhaust the H^+ decay width, but the relative branching ratio is free. Thus, the searches encompass the following $\mathrm{H}^+\mathrm{H}^-$ final states: $(\mathrm{c\bar{s}})(\mathrm{c\bar{s}})$, $(\tau^+\nu)(\tau^-\bar{\nu})$ and the mixed mode $(\mathrm{c\bar{s}})(\tau^-\bar{\nu})+(\mathrm{\bar{c}s})(\tau^+\nu)$. The combined search results are presented as a function of the branching ratio B($\mathrm{H}^+ \to \tau^+\nu$).

The data collected by the four LEP experiments at energies from 189 to 209 GeV have been analysed and combined [23]. Details of the searches of the individual experiments can be found in [25,26]. It should be noted that L3 observes an excess of events in the pure hadronic and the semi-leptonic channels in the mass region around 68 GeV [26]. The compatibility of the L3 and the three other experiments observations in the vicinity of 68 GeV is under investigation.

The mass limits expected and observed are shown in Figure 6. To obtain the limits, the branching ratio B($\mathrm{H}^+ \to \tau^+\nu$) has been scanned in steps of 0.05, and the limit setting procedure repeated for each step. In the hadronic channel and for masses close to $m_{\mathrm{W}^\pm}$, the sensitivity is suppressed by the large $\mathrm{e}^+\mathrm{e}^- \to \mathrm{W}^+\mathrm{W}^-$ background. There is a regain of sensitivity at higher masses, as signalled by the excluded "islands" above 84 GeV. A 95% C.L. lower bound of 78.6 GeV for the mass of the charged Higgs boson is obtained.

5. Conclusions

The LEP experiments have sought many different signatures of Higgs bosons beyond the Standard Model, in particular in 2HDM scenarios without observing a compelling evidence of new physics. Exclusion limits at 95% C.L. have been extracted. For tan$\beta \geq 0.4$ the region $1 \leq m_{\mathrm{h}} \leq 58$ GeV with $10 \leq m_{\mathrm{A}} \leq 65$ GeV is excluded at 95% C.L. by an OPAL study in the most general 2HDM(II) with no CP-violation in the Higgs sector. A lower limit on the charged Higgs mass of 78.6 GeV is obtained by the combined searches of all LEP experiments. Limits on the Yukawa production of Higgs have been set by the LEP collaborations, which are interpreted to restrict the possible contribution from the Higgs sector to the anomalous magnetic moment of the muon. In view of the next generation of colliders the LEP results on 2HDMs provide a crucial indication on the parameter space regions where new physics could be sought and eventually found.

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