Standard Model and Supersymmetry Higgs searches at LEP

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Abstract

In the year 2000 the four LEP experiments have collected data at centre-of-mass energies between 200 and 209 GeV, integrating about 870 pb^{-1} of luminosity, with about 510 pb^{-1} above 206 GeV. Searches for the Standard Model and supersymmetric bosons have been performed by each LEP collaboration. The results presented here are combinations of preliminary results from the four LEP experiments.

1 Introduction

The Higgs mechanism plays a crucial role in the unification of the electromagnetic and weak interactions by providing mass to the intermediate vector bosons, W and Z, without violating local gauge invariance. Within the Standard Model (SM), the Higgs mechanism predicts a single neutral scalar particle, the Higgs boson. In supersymmetric models (SUSY) a minimum of five Higgs bosons (three neutral and two charged bosons) is predicted.

Since 1996, LEP has delivered an integrated luminosity of about 700 pb^{-1} per experiment at centre-of-mass energies ($\sqrt{s}$) larger than 160 GeV (above the W-pair production threshold) and up to 209 GeV, and direct searches for SM and SUSY Higgs bosons have been performed by the four LEP experiments in the collected data.

This paper is organized as follows: The first part reports on the search for a SM Higgs boson, summarizing the analysis procedure before quoting the results. In the second part the search for SUSY neutral and charged Higgs bosons is addressed. All results presented here are discussed in detail in references [1] to [6].

2 Standard Model Higgs boson [1]

2.1 Introduction

Measurements of the electroweak parameters depend in their interpretation on the logarithm of the Higgs boson mass via radiative corrections. If the Standard Model is assumed, indirect experimental constraints derived from precision measurements of electroweak parameters lead to $m_H = 88^{+53}_{-33}$ GeV/c^2. The SM Higgs boson could then be accessible at LEP2.

Before the year 2000, direct searches carried out by the four LEP collaborations did not reveal any signal for the SM Higgs boson. The situation has changed in summer 2000, when centre-of-mass energies have reached 206 GeV. As much as 210 pb^{-1} per experiment was delivered in the year 2000 at $\sqrt{s}$ above 206 GeV.

The main production process for the SM Higgs boson at energies within LEP2 reach is the Higgs-strahlung process, $e^+e^- \to Z^* \to HZ$, which gives access to Higgs masses as large as $M_H \sim (\sqrt{s} - M_Z)$.

The final state topologies are determined by the Higgs decay and by the decay of the associated Z boson. Because of its suppressed couplings to light fermions, the dominant decay mode of the Higgs boson with masses around 100 to 120 GeV/c^2 is into $b\overline{b}$ (branching ratio as large as 75 %). One therefore expects four main final states, which are then studied in four different search channels: the four-jet channel (50 to 60 %) when $H \to b\overline{b}$ and $Z \to q\overline{q}$; the tau channel (10 %) when $H \to b\overline{b}$ and $Z \to \tau^+\tau^-$ or $H \to \tau^+\tau^-$ and $Z \to q\overline{q}$, which gives rise to two jets and two tau final states; the missing energy channel ($\sim$17 %) when $H \to b\overline{b}$ and $Z \to \nu\overline{\nu}$, which gives two jets and missing energy; and the leptonic channel ($\sim$6 %) when $H \to b\overline{b}$ and $Z \to e^+e^-$ or $\mu^+\mu^-$, giving rise to two jets and two leptons.

At LEP2, backgrounds arise mainly from Z pair and W pair productions which give final state topologies similar to the signal ones. Another serious background comes from $q\overline{q}$ production with either final-state gluon radiation (giving a four-jet topology) or initial-state photon radiation where the photon is lost in the beam pipe (giving a two-jet plus missing energy topology). The cross-section of the various background processes as a function of centre-of-mass energy are shown on figure 1 together with the expected Higgs-strahlung process cross-sections for a Higgs boson mass between 60 GeV/c^2 and 115 GeV/c^2.

2.2 Analysis strategy and statistical method

In the following I shall explain the analysis strategy adopted by the experiments [1]. Although the implementation of the selections and analysis procedure is different for each experiment, the general strategy is common to all four. It consists of three parts. First, in order to reduce the main background coming from two photon processes and from radiation return to the Z, a soft preselection is applied on kinematic variables such as the visible energy and the number of charged tracks. Then a likelihood selection is applied to reduce background from fermion pair production ($e^+e^- \to f\overline{f}$) possibly with photon or gluon radiation, W pair production and Z pair production. The likelihood selection is based on the kinematic differences between signal and background processes and makes also extensive use of b-tagging, as the b-flavour is abundant in the decay of the Higgs boson. The third part consists in using discriminating variables: the reconstructed Higgs boson mass (M_H), on the one hand, and the likelihood value obtained in the likelihood selection, on the other hand. Figure 2 shows the reconstructed Higgs boson mass from the data collected by the four LEP experiments in the year 2000, after applying three special non-biasing selections (loose, medium and tight) with increasing signal purity. Although a slight excess becomes visible at high masses in the tight selection, no conclusion should be drawn at this stage. The reconstructed mass does not contain all the information available and it is important to use other discriminating variables such as kinematic ones and the b-flavour content of the events.

The four LEP experiments therefore use a statistical method which I explain briefly in what follows. The events are binned into two discriminating variables: the reconstructed

Higgs mass and the likelihood value which is a global variable containing information about kinematics, b-tagging, etc... For each bin one obtains three numbers: the expected background rate (b_i), obtained from Monte Carlo simulation, the expected signal for a set of hypothesized Higgs boson masses M_{H} ($s_i(M_{\mathrm{H}})$), and the number of selected data events. For a given test-mass M_{H}, a weight s/b can thus be assigned to each selected candidate depending on M_{H} and on the bin where it is reconstructed.

Two hypotheses are considered: the background-only hypothesis (b), where it is assumed that data receives contributions from the SM background processes only; and the signal+background hypothesis ($s+b$), where the contribution from a Higgs boson of test mass M_{H} is assumed in addition. A statistical estimator allowing to rank any data configuration between the background and signal+background hypotheses is then defined as $Q(M_{\mathrm{H}})$, a likelihood ratio for the test mass M_{H}. It is simply the ratio of the Poisson probabilities for the signal+background hypothesis $\mathcal{L}(s+b)$ and for the background-only hypothesis $\mathcal{L}(b)$:

$$Q(M_{\mathrm{H}}) = \frac{\mathcal{L}(s+b)}{\mathcal{L}(b)} \approx \frac{e^{-(s+b)}}{e^{-b}} \prod_{i=1}^{N_{cand}} \frac{s_i(M_{\mathrm{H}}) + b_i(M_{\mathrm{H}})}{b_i(M_{\mathrm{H}})},$$

where the product runs over the number of candidates observed in data (N_{cand}), and s and b are the total expected signal and background rates. For convenience, the logarithm of $Q(M_{\mathrm{H}})$ is used:

$$-2\ln Q(M_{\mathrm{H}}) = 2s - 2\sum_{i=1}^{N_{cand}} N_i \ln(1 + \frac{s_i(M_{\mathrm{H}})}{b_i(M_{\mathrm{H}})}).$$

As an illustration, figure 3 shows the expected distributions for $-2\ln Q(M_{\mathrm{H}})$ for a given test mass M_{H} for two types of simulated experiments: experiments observing only background (distribution labelled "b") and experiments observing a signal in addition to background (distribution labelled "s+b"). The separation of the two distributions is a measure of the sensitivity of a search for a signal with mass M_{H}. The value of $-2\ln Q(M_{\mathrm{H}})$ obtained with data (shown as the line labelled "observed") gives a measure of the background-only or signal+background likeliness of the data. The area CL_{sb} shown on figure 3 represents the compatibility of data with the signal+background hypothesis for a given value of M_{H}. Given an ensemble of signal+background experiments, CL_{sb} is the probability to obtain an event configuration more background-like than the observed event configuration. The larger CL_{sb} the more likely there is a signal. Similarly, the area $(1 - CL_b)$ represents the compatibility of data with the background-only hypothesis. Given an ensemble of background-only experiments, $(1 - CL_b)$ is the probability to obtain an event configuration less background-like than the observed event configuration. The larger $(1 - CL_b)$ the more likely there is a signal (the less likely it is only background).

2.3 Results

The results obtained at LEP2 combining all four experiments are presented thoroughly in Ref [1], and are shown on figures 4 and 5. Figure 4 shows $-2\ln Q(M_{\mathrm{H}})$ as a function of M_{H}. The dashed and dash-dotted curves are the expectations for background-only and for signal+background hypotheses respectively. The dark and light shaded areas represent the 1σ and 2σ bands around the background expectation. The solid curve is the observed one (obtained with data). It shows a minimum for $M_{\mathrm{H}} = 115.6$ GeV/c^2 which indicates a deviation from the background hypothesis. This minimum coincides with the signal+background expectation for the same test mass. Also shown on figure 4 is the expectation for signal+background with a Higgs mass of 115 GeV/c^2 (dotted curve).

Figure 5 presents the results in a different view: it shows $(1-CL_b)$ as a function of M_{H}. Again, the continuous curve is observation, and the dashed and dash-dotted curves are the background-only and signal+background expectations. The largest deviation (about 2σ) is obtained for $M_{\mathrm{H}} = 115.6$ GeV/c^2. For this M_{H} value, the probability of a background fluctuation is as low as 3.5% for the four LEP experiments. This value, however, is mainly driven by ALEPH which has a very signal-like observation $(1 - CL_b = 0.23\%)$. On the other hand, OPAL and L3 show only a slight excess $(1-CL_b = 22\%$ and 23% respectively) and DELPHI has a very background-like observation $(1 - CL_b = 88\%)$. In addition the signal-like behaviour in the vicinity of 115 GeV/c^2 in the ALEPH data is concentrated in the four-jet final state channel. The other three final state topologies do not present any excess.

The ratio $CL_s = \frac{CL_{sb}}{CL_b}$ as a function of test mass is used to derive a lower bound for the SM Higgs boson mass. A value of CL_s=0.05 gives the 95% confidence level (CL) lower bound on M_{H}. The mass limit obtained with the four LEP experiments is 114.1 GeV/c^2 at 95% CL. The slight excess which is observed in the ALEPH experiment corresponds to a preferred mass of 115.6 GeV/c^2. Finally, the mass limit obtained with DELPHI, L3 and OPAL combined is 114.8 GeV/c^2 at 95% CL, which therefore does not exclude the ALEPH excess.

3 Supersymmetric Higgs bosons

In the SM, only one complex Higgs doublet is present, giving rise to only one physical neutral Higgs scalar, whose mass is a free parameter. It is interesting to consider more complicated models. Among these, the Two Higgs Doublet Models (2HDM) are attractive as they add new phenomena, they add the fewest new arbitrary parameters, and such a Higgs structure is required in low-energy Supersymmetry models. There are five physical Higgs bosons in 2HDM: two neutral CP-even scalars (h^0 and H^0), one CP-odd scalar (A^0) and two charged scalars ($\mathrm{H}^{\pm}$). If no CP-violation is considered, there are six free parameters in 2HDM: four masses (M_{h}, M_{H}, M_{A} and $M_{\mathrm{H}^{\pm}}$) and two angles (α, the mixing angle between h^0 and H^0, and $\tan\beta$, the ratio of vacuum expectation values of the two Higgs doublets).

At LEP2 various searches for Supersymmetric Higgs bosons have been performed [2, 3, 4, 5, 6]. In the following I will concentrate on the search for neutral Higgs bosons (h^0, H^0 and A^0). Then I will present the results of searches for charged Higgs bosons (H^+ and H^-). Finally, the results of special searches for "invisible" or "photonic" Higgs bosons are briefly outlined.

3.1 Neutral Higgs bosons [2, 3]

3.1.1 Introduction

The main neutral Higgs boson production processes are the Higgs-strahlung process $e^+e^- \to Z^* \to h^0Z$ or H^0Z. The Higgs-strahlung process for h^0 production proceeds as in the SM, but its rate is suppressed by the factor $\sin^2(\beta - \alpha)$. When kinematically allowed, the Higgs-strahlung process for H^0 production also proceeds as in the SM, but with a rate suppressed by $\cos^2(\beta - \alpha)$. It may therefore happen that the production cross-section σ_{H^0Z} is larger than σ_{h^0Z}. In addition, the process $e^+e^- \to Z^* \to h^0A^0$ may also occur when kinematically allowed, and its production cross-section $\sigma_{h^0A^0}$ is proportional to the SM cross-section for the Higgs-strahlung process and to $\cos^2(\beta - \alpha)$. These three processes are considered in the searches presented here.

The decay branching ratios of the Higgs bosons to fermions depend on the masses, but also on α and β. For example, at tree level, the couplings of h^0 to $c\bar{c}$ and to $b\bar{b}$ are proportional to $\frac{\cos\alpha}{\sin\beta}$ and $-\frac{\sin\alpha}{\cos\beta}$, and the couplings of A^0 to $c\bar{c}$ and to $b\bar{b}$ are proportional to $\cot\beta$ and $\tan\beta$. Over much of the parameter space considered, h^0 and A^0 decay predominantly into $b\bar{b}$ or $\tau\tau$.

In the h^0Z analysis, four search topologies are considered in the analyses. They are identical to the SM channels, with the SM Higgs replaced by h^0. In addition, for models in which the decay branching ratios of the Higgs bosons to $b\bar{b}$ and $\tau\tau$ are suppressed (for low values of α and β), flavour-independent analyses are performed. In the h^0A^0 analysis, two main topologies occur: the four-jet final state, when both h^0 and A^0 decay into $b\bar{b}$, and the final state with two jets and two tau leptons when either h^0 or A^0 decays into $b\bar{b}$ and the other one into $\tau\tau$. These topologies give rise to two analyses: the four-jet channel and the tau channel as in the SM Higgs search, but with no M_Z constraint.

The LEP experiments test for the presence of an MSSM (Minimal Supersymmetric extension of the Standard Model) Higgs boson signal using a constrained model with seven parameters: $\tan\beta$ (the ratio of the vacuum expectation values of the two Higgs doublets), M_{SUSY} (the SUSY breaking sfermion masses), M_2 (the SUSY breaking gaugino masses), μ (the SUSY Higgs boson mass parameter), A_0 (the common trilinear Higgs-squark coupling parameter), M_g (the gluino mass) and M_A (the mass of the CP-odd Higgs boson).

Three benchmark scenarios are considered:

- A scenario with no mixing between the scalar partners of the left-handed and the right-handed top quarks ("no mixing" scenario). In this benchmark scenario, $M_{SUSY} = 1$ TeV/c^2, $M_2 = 200$ GeV/c^2, $\mu = -200$ GeV/c^2, $X_t \equiv A_0 - \mu\cot\beta = 0$, $0.4 < \tan\beta < 30$, $M_g = 800$ GeV/c^2 and 4 GeV/c$^2 < M_A < 1$ TeV/c^2.

- A scenario with large mixing in the stop sector ("maximal M_H" scenario). The MSSM parameter values and ranges are the same as for the "no mixing" scenario, except for $X_t \equiv A_0 - \mu\cot\beta$ which is $2M_{SUSY}$. This benchmark scenario involves an extended parameter space, and is such that the maximum possible Higgs boson mass as a function of $\tan\beta$ is obtained, therefore giving the most conservative limits. It correspond to the most conservative range of excluded $\tan\beta$ values for fixed values of M_{SUSY}.

- A “large μ” scenario. This scenario is designed to illustrate choices of MSSM parameters for which the Higgs boson h^0 does not decay into pairs of b quarks, but rather into $c\bar{c}$, gg, W^+W^-, $\tau^+\tau^-$, etc ..., due to large corrections from Supersymmetry loop processes. Its study requires a flavour independent analysis. Here M_{SUSY} = 400 GeV/c^2, M_2 = 400 GeV/c^2, μ = 1 TeV/c^2, X_t = −300 GeV/c^2, $M_{\rm g}$ = 200 GeV/c^2 and 4 GeV/c^2 $< M_{\rm A} <$ 400 GeV/c^2.

The statistical method adopted for the combination of the data and the definitions of the test-statistic $\ln Q(M_{\rm H})$ and the confidence levels CL_b, CL_{sb} and CL_s are as for the SM Higgs search. In the following are presented results obtained using data collected between 88 GeV and 209 GeV centre-of-mass energies (data collected in the year 2000 combined with all previous LEP data). All results are given in Ref [2]. In the following I shall give only a few of them, serving as an example.

3.1.2 Results

On figure 6 is shown the $(1 - CL_b)$ significance contours as a function of $M_{\rm h}$ and $M_{\rm A}$ for the “maximal $M_{\rm H}$” benchmark scenario. In the white area, the observation either shows a deficit or is less than 1σ above the background prediction. In the areas labelled “$\geq 1\sigma$” and “$\geq 2\sigma$”, on the other hand, the observation shows an excess above the SM background: $(1 - CL_b) < 0.32$ for the “$\geq 1\sigma$” area and $(1 - CL_b) < 0.05$ for the “$\geq 2\sigma$” area.

The small area around $M_{\rm h}$ = 83 GeV/c^2 and $M_{\rm A}$ = 83 GeV/c^2 corresponds to a $\sim 2\sigma$ excess in the $e^+e^- \to h^0A^0$ searches due to candidates in the OPAL $\tau\tau b\bar{b}$ channel in the data collected at $\sqrt{s}$ = 189 GeV, which have not been confirmed by later running or in other experiments. The significance has gradually decreased as additional luminosity has been accumulated.

The small area around $M_{\rm h}$ = 93 GeV/c^2 and $M_{\rm A}$ = 93 GeV/c^2 also corresponds to a $\sim 2\sigma$ excess in the $e^+e^- \to h^0A^0$ searches due to candidates in the OPAL four-jet channel in data taken in the year 2000, which, again, does not appear in other samples.

The two thin bands around $M_{\rm h}$ = 97 GeV/c^2 and $M_{\rm h}$ = 115 GeV/c^2 correspond to $\geq 2\sigma$ excesses in the $e^+e^- \to h^0Z$ searches. The first one is present in the $\sqrt{s}$ = 189 GeV data but not in higher centre-of-mass energy data.

The 95% CL exclusion contour is also shown on figure 6, as a dashed line. Points to the right and below this curve are not excluded. It gives mass limits of $M_{\rm h} <$ 91.0 GeV/c^2 (when 95.0 GeV/c^2 is expected in background-only experiments) and $M_{\rm A} <$ 91.9 GeV/c^2 (when 94.6 GeV/c^2 is expected).

The same results can be shown in terms of different parameters: for example figures 7 and 8 show the 95% CL exclusion region in the ($M_{\rm A}$,$\tan\beta$) and the ($M_{\rm H^\pm}$,$\tan\beta$) planes. Limits on $\tan\beta$ are determined by the exclusion limit for the h^0Z process which depends strongly on the centre-of-mass energies. Values of $\tan\beta$ between 0.5 and 2.4 are excluded at 95% CL.

Figure 9 shows the 95% CL exclusion region as a function of $M_{\rm A}$ and $\tan\beta$ for the “no mixing” benchmark scenario. In this scenario $\tan\beta$ values are excluded between 0.7 and 10.5. The lower limit is determined by the lack of sensitivity to the process $e^+e^- \to h^0Z \to A^0A^0Z$ where the A^0 does not decay to $b\bar{b}$ either because $\tan\beta$ is too small or because A^0 is too light. The upper limit is determined by the kinematic sensitivity of the $e^+e^- \to h^0A^0$ searches which leave an unexcluded region for 90 GeV/c^2 $< M_A <$ 120 GeV/c^2. In this region, Higgs-strahlung is suppressed by $\sin^2(\beta - \alpha)$ and h^0A^0 is kinematically out of reach. For $\tan\beta > 0.7$, one gets lower limits on M_A and M_h of 92.2 GeV/c^2 and 91.5 GeV/c^2 respectively.

On figure 10 is shown the exclusion region in terms of M_h and M_A. Two areas are unexcluded: one occurs for $M_h > 91.5$ GeV/c^2 and $M_A > 92.2$ GeV/c^2 and the other one for M_h larger than 65 GeV/c^2 and M_A smaller than 40 GeV/c^2. This second non-exclusion region corresponds to $\tan\beta < 0.7$ and $M_{H^\pm} < 74$ GeV/c^2 and is due, as mentionned above, to the lack of sensitivity to the process $e^+e^- \to h^0Z \to A^0A^0Z$ with no $A^0 \to b\bar{b}$ decay.

The third benchmark scenario, "large μ" scenario, addresses extensions of the SM in which the Higgs bosons have suppressed couplings to b quarks. Flavour-independent searches (not using b-tagging) are performed. The same statistical techniques are used as in the SM Higgs search. The observed and expected confidence levels for signal and for background-only hypotheses are very consistent.

Figure 11 shows CL_s as a function of M_h for the observation (dotted line) and the expectation for the background-only hypothesis (dashed line). The observed and expected limits are 112.9 GeV/c^2 and 113.0 GeV/c^2 respectively. The "large μ" scenario is entirely excluded.

3.2 Charged Higgs bosons [4]

The four LEP experiments have also searched for pair production of charged Higgs bosons ($e^+e^- \to H^+H^-$) [4]. In doing so, it is assumed that the two decays $H^+ \to c\bar{s}$ and $H^+ \to \tau\nu$ exhaust the decay width, but the relative branching ratio remains free ($BR(H^+ \to c\bar{s}) + BR(H^+ \to \tau\nu) = 1$). Three topologies are therefore considered: the four-jet channel (cscs), the leptonic channel ($\tau\tau\nu\nu$) and the semileptonic channel (cs$\tau\nu$). The search results are presented as a function of BR, as shown on figure 12, giving the exclusion region at 95% CL as a function of $BR(H^+ \to \tau\nu)$ and $M_{H^\pm}$. For small values of $BR(H^+ \to \tau\nu)$, the searches loose sensitivity around $M_{H^\pm} = 81$ GeV/c^2 due to the irreducible W pair background, but regain sensitivity above 82 GeV/c^2.

The charged Higgs boson mass limits obtained are 81.0 GeV/c^2 for $BR(H^+ \to \tau\nu) = 0$, 89.6 GeV/c^2 for $BR(H^+ \to \tau\nu) = 1$ and 78.6 GeV/c^2 for any value of $BR(H^+ \to \tau\nu)$.

3.3 "Invisible" and "photonic" Higgs bosons [5, 6]

As discussed in Ref [5], a specific analysis has been developed for searching for a Higgs boson decaying into invisible particles, such as $\tilde{\chi}^0_1$, the lightest neutralino, if it is the LSP (Lightest Supersymmetric Particle). In the process $e^+e^- \to h^0Z$, even though the h^0 may be invisible, its presence can be inferred from the presence of the Z.

Two situations are considered, where the Z decays into either a pair of quarks or a pair of charged leptons, giving rise to two topologies: a pair of acoplanar jets or a pair of acoplanar leptons. The search has given a lower mass limit of 114.4 GeV/c^2 at 95% CL for an "invisible" Higgs boson, while the expected mass limit is 113.5 GeV/c^2.

Another specific analysis [6] was used for searching for fermiophobic Higgs bosons, that is, Higgs bosons not decaying into a pair of fermions. Only $h^0 \rightarrow \gamma\gamma$ (photonic Higgs boson) has been considered by the four LEP experiments. Assuming the SM Higgs boson production rate, a lower limit of 108.2 GeV/c^2 has been obtained for the photonic mass (with an expected limit of 109.0 GeV/c^2, and an upper limit of 6% has been obtained for the branching ratio BR($h^0 \rightarrow \gamma\gamma$), at 95% CL.

4 Conclusions

Direct searches for a Sm Higgs boson have been performed by the four LEP collaborations. A lower limit of 114.1 GeV/c^2 has been obtained for its mass. However, a slight excess (2σ effect) has been observed at a mass of 115.6 GeV/c^2, dominated by one of the four experiments.

In addition, supersymmetric Higgs bosons have also been searched for. The negative results have been interpreted in terms of exclusion regions in the SUSY parameter space.

References

[1] ALEPH, DELPHI, L3 and OPAL Collaborations and the LEP Working Group for Higgs Boson Searches, "Search for the Standard Model Higgs Boson at LEP", LHWG Note/2001-03,CERN-EP/2001-055, contributed paper to EPS'01, Budapest, and LP'01, Rome, 2001. And references therein.

[2] ALEPH, DELPHI, L3 and OPAL Collaborations and the LEP Working Group for Higgs Boson Searches, "Searches for the Neutral Higgs Bosons of the MSSM: Preliminary Combined Results using LEP Data Collected at Energies up to 209 GeV", LHWG Note/2001-04, contributed paper to EPS'01, Budapest, and LP'01, Rome, 2001. And references therein.

[3] ALEPH, DELPHI, L3 and OPAL Collaborations and the LEP Working Group for Higgs Boson Searches, "Flavour Independent Search for Hadronically Decaying Neutral Higgs Bosons at LEP", LHWG Note/2001-07, contributed paper to EPS'01, Budapest, and LP'01, Rome, 2001.

[4] ALEPH, DELPHI, L3 and OPAL Collaborations and the LEP Working Group for Higgs Boson Searches, "Search for the Charged Higgs Bosons: Preliminary Combined Results using LEP data Collected at Energies up to 209 GeV", LHWG Note/2001-05, contributed paper to EPS'01, Budapest, and LP'01, Rome, 2001.

[5] ALEPH, DELPHI, L3 and OPAL Collaborations and the LEP Working Group for Higgs Boson Searches, "Searches for Invisible Higgs bosons: Preliminary combined results using LEP data collected at energies up to 209 GeV", LHWG Note/2001-6, contributed paper to EPS'01, Budapest, and LP'01, Rome, 2001.

[6] ALEPH, DELPHI, L3 and OPAL Collaborations and the LEP Working Group for Higgs Boson Searches, "Search for the Higgs Bosons Decaying into Photons: Preliminary Combined Results using LEP Data Collected at Energies up to 209 GeV", LHWG Note/2001-08, contributed paper to EPS'01, Budapest, and LP'01, Rome, 2001.

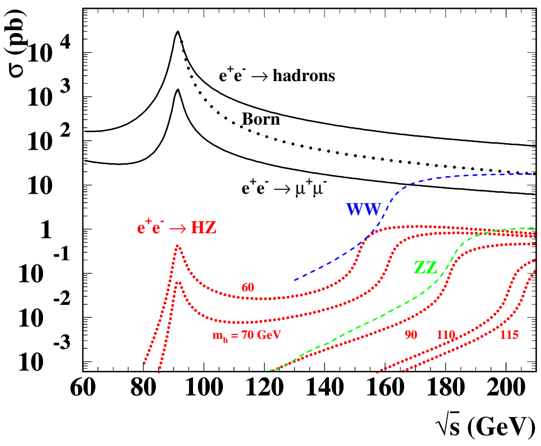

Figure 1: Cross-section of the various SM background processes as a function of centre-of-mass energy. Also shown are the cross-section of the Higgs-strahlung process for SM Higgs boson with various masses.

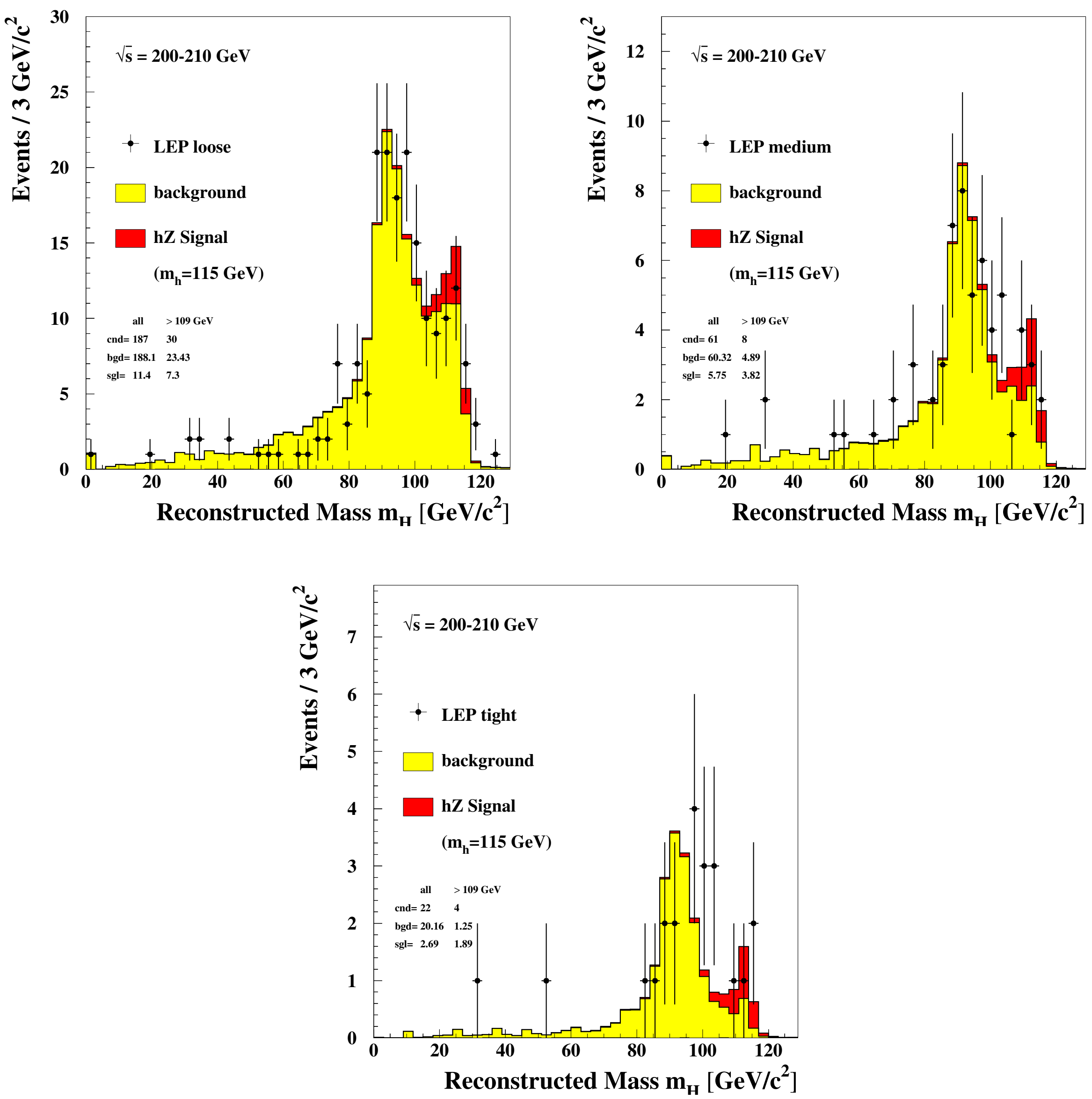

Figure 2: Distributions of the reconstructed Higgs mass from three special, non-biasing, selections with increasing purity of a signal from a 115 GeV/c^2 Higgs boson.

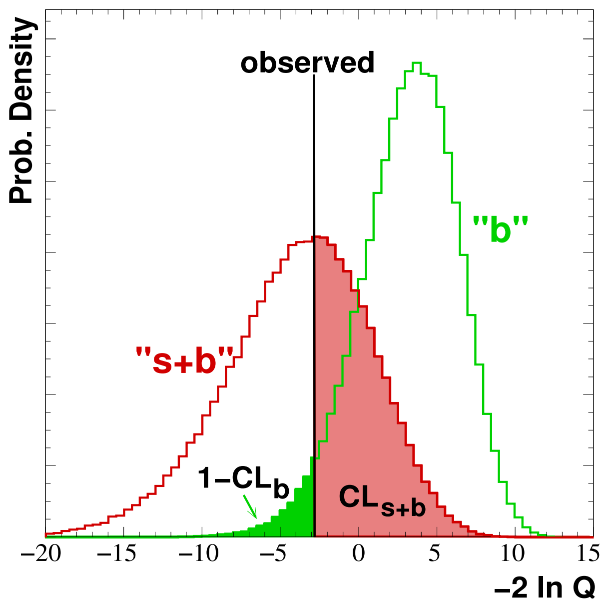

Figure 3: Probability density functions corresponding to a test-mass $M_{\mathrm{H}} = 115.6\ \mathrm{GeV/c}^2$ for the background-only and signal+background hypotheses.

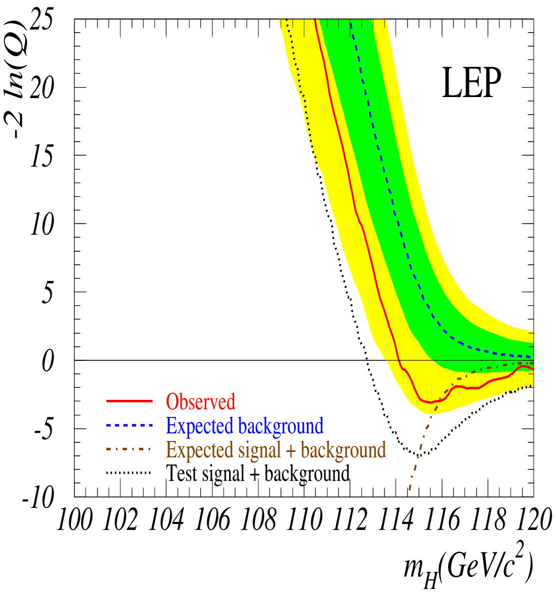

Figure 4: Observed and expected behaviour of $\ln Q(M_{\mathrm{H}})$ as a function of test-mass M_{H}, obtained by combining the data of all four experiments.

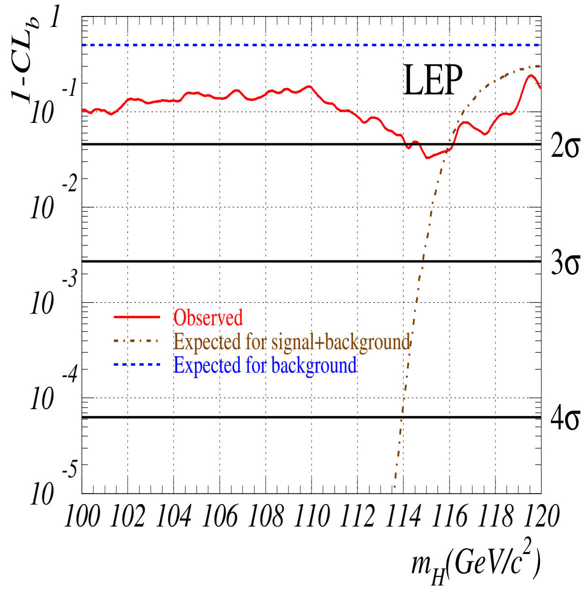

Figure 5: The probability $(1 - CL_b)$ as a function of the test-mass M_{H}.

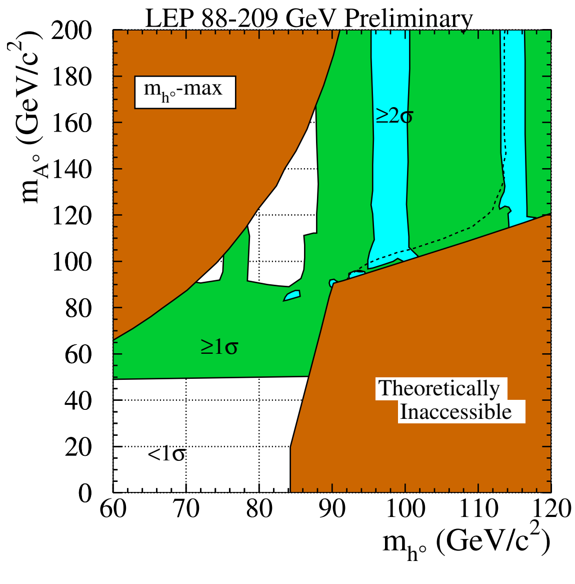

Figure 6: The distribution of the confidence level CL_b in the $(M_{\mathrm{h}}, M_{\mathrm{A}})$ plane for the "maximal M_{H}" benchmark scenario.

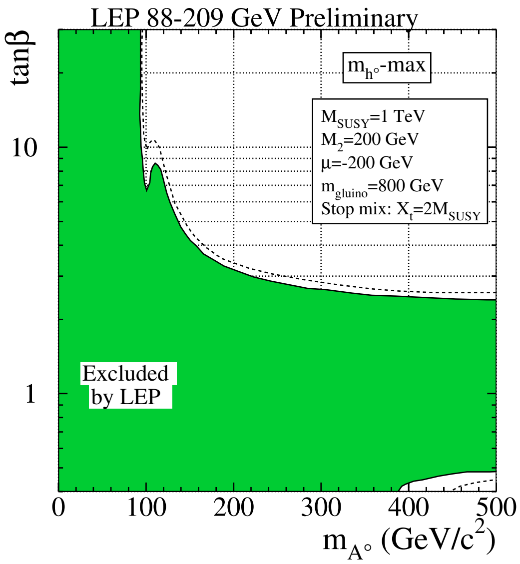

Figure 7: The MSSM exclusion for the “maximal M_{H}” benchmark scenario in the $(M_{\mathrm{A}}, \tan\beta)$ plane.

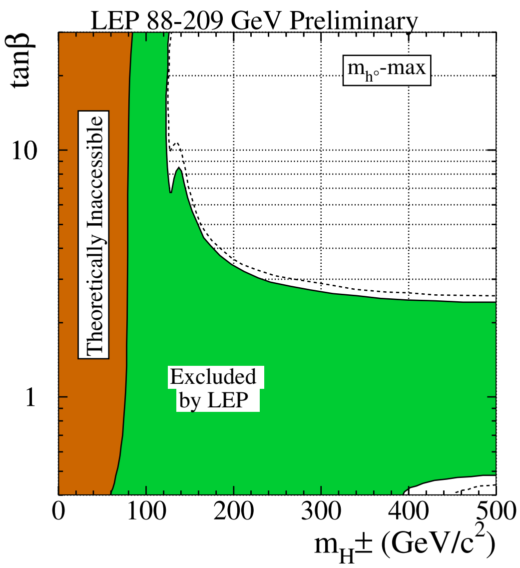

Figure 8: The MSSM exclusion for the “maximal M_{H}” benchmark scenario in the $(M_{\mathrm{H}^\pm}, \tan\beta)$ plane.

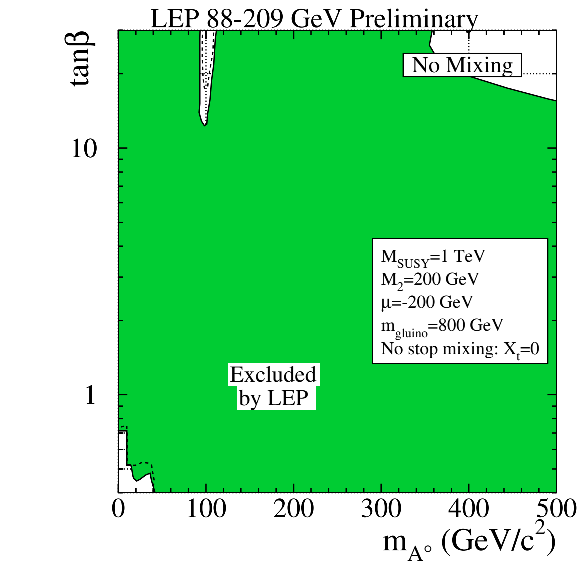

Figure 9: The MSSM exclusion for the "no mixing" benchmark scenario in the $(M_{\mathrm{A}}, \tan\beta)$ plane.

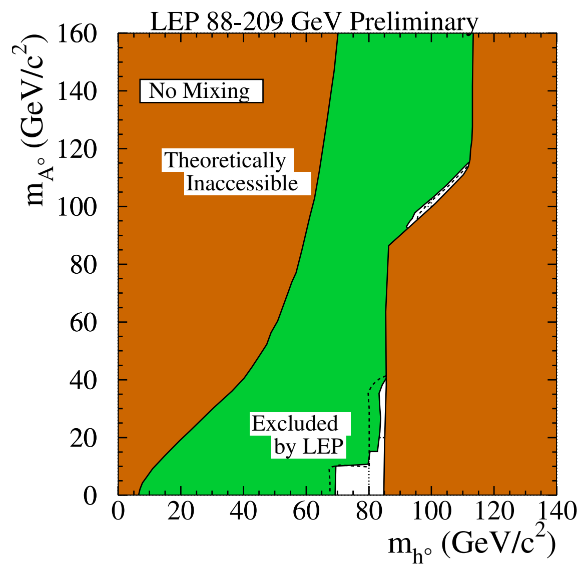

Figure 10: The MSSM exclusion for the "no mixing" benchmark scenario in the $(M_{\mathrm{h}}, M_{\mathrm{A}})$ plane.

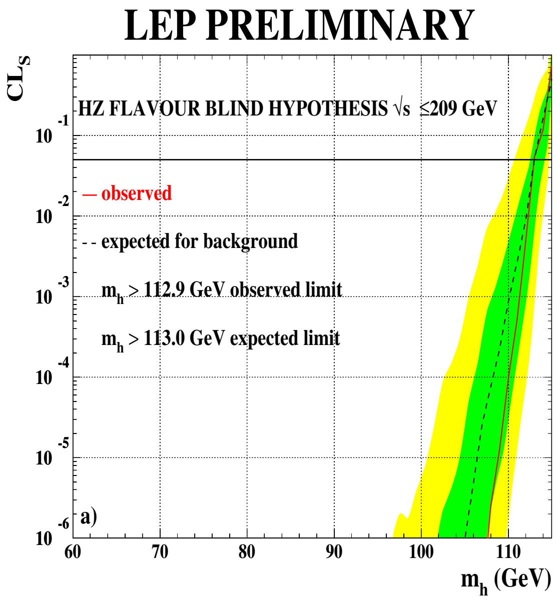

Figure 11: Combined LEP confidence levels as a function of the Higgs boson mass in the flavour independent hypothesis, assuming production cross-sections equal to those in the SM and BR($h^0 \rightarrow$ hadrons) = 1.

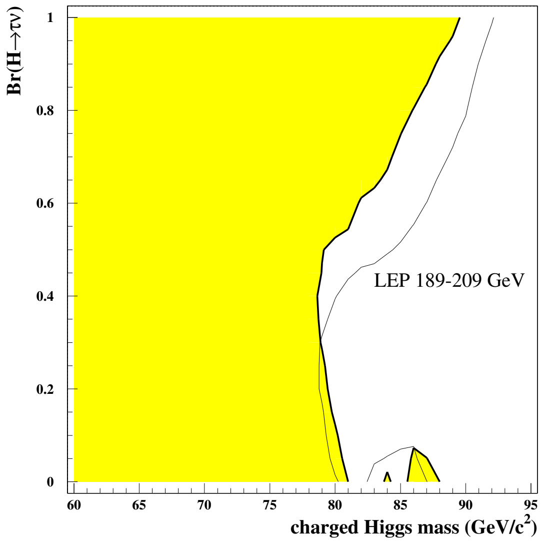

Figure 12: The 95% CL bounds on $M_{H^\pm}$ as a function of the branching ratio BR($H^+ \rightarrow \tau\nu$), combining the data collected by the four LEP experiments at energies from 189 to 209 GeV. The expected exclusion limits are indicated by the thin solid line and the observed limits by the thick solid line. The shaded are is excluded at the 95% CL.