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Search for Charged Higgs Bosons

M. Battaglia, M. Ellert, T. Ekelöf, G. Gómez-Ceballos, A. Kiiskinen, P. Lutz and F. Matorras

Abstract

A search for pair produced charged Higgs bosons has been performed in the high energy data collected by the DELPHI detector at LEP II at centre-of-mass energies up to 189 GeV. Analyses of three different final states, $\tau\nu\tau\nu$, $c\bar{s}\tau\nu$ and $c\bar{s}\bar{c}s$ are included. New methods have been applied in the rejection of wrong hadronic jet pairings and for the tau identification, where a discriminator based on tau polarisation and polar angles was used. The data analysed has been found to be compatible with the expected background. The results are given as lower mass limits as a function of the leptonic branching ratio.

1 Introduction

The existence of a charged Higgs boson doublet is predicted by several extensions of the Standard Model. Pair production of charged Higgs bosons occurs mainly via s-exchange of a photon or a Z boson. In two-doublet models, the couplings are completely specified in terms of the electric charge and the Weinberg angle, θ_W, and therefore the production cross section depend only on the charged Higgs boson mass. Higgs bosons decay predominantly to the heaviest fermions kinematically allowed, which in the case of charged Higgs bosons can be $\tau\nu_\tau$ or cs pairs.

A search for pair-produced charged Higgs bosons has been performed based on the data collected by DELPHI during the LEP runs at centre-of-mass energies $\sqrt{s}$ of 183 GeV and 189 GeV. The results reported in this paper supersede those obtained in an earlier analysis of the DELPHI data limited to the 183 GeV runs [1]. Similar searches have been performed by the other LEP experiments [2].

A new technique has been developed to improve the discrimination against the hadronic W decays in the search for $H^\pm$ candidates. Also new methods using the tau polarisation and boson production angles have been used.

In section 2 the event reconstruction and the definition of the discriminating variables are discussed separately for the leptonic, hadronic and mixed final states with particular emphasis on the $\sqrt{s} = 189$ GeV data. Section 3 describes the results from the combined DELPHI data at LEP II.

2 Data Analysis

The analysis has been performed on the data collected by the DELPHI detector at LEP-II at centre-of-mass energies of 183 GeV and 189 GeV. The DELPHI detector and its performance have already been described in detail elsewhere [3, 4].

Signal samples have been simulated using the PYTHIA generator [6]. The background estimates from the different Standard Model processes are based on the following event generators: PYTHIA is used to generate $q\overline{q}(\gamma)$, KORALZ [12] for $\mu^+\mu^-$ and $\tau^+\tau^-$, BAFO [13] for e^+e^-, four-fermion final states from ZZ, WW, Weν_e and Zee processes have been also generated with PYTHIA and two-photon interactions have been generated with TWOGAM [14] for hadronic final states, BDK [15] for electron final states and BDKRC [15] for other leptonic final states. In hadronic and mixed channels EXCALIBUR generator [7] has been used for the simulation of four fermion final states.

2.1 The leptonic channel

The signature for $H^+H^- \to \tau^+\nu_\tau\tau^-\overline{\nu}_\tau$ is a pair of tau leptons, characterised by low multiplicity with a clean two-jet topology with two energetic, acollinear and acoplanar leptons of opposite charge and, large missing momentum and energy. The analysed data was collected by DELPHI at centre-of-mass energies of 183 GeV and 189 GeV during periods of good running for the most important sub-detectors used in this analysis in order to ensure good quality of events, corresponding to integrated luminosities of 47.0 pb^{-1} and 153.8 pb^{-1}.

Charged particle tracks have been required to satisfy the following criteria. Only particles with momentum larger than 200 MeV/c^2, relative momentum error $\Delta P/P < 1$, track length greater than 20 cm and polar angle with respect to the beam direction $10^\circ < \theta < 170^\circ$ have been used. In addition, the impact parameter w.r.t. the event primary vertex has to be smaller than 4.0 cm.

An initial set of cuts has been applied to select a sample enriched in leptonic events. All particles in the event have been clustered into jets using the LUCLUS algorithm [6] (d_{join}=6.5 GeV/c^2) and only events with two reconstructed jets, containing at least one charged particle each, have been retained. A charged particle multiplicity between 2 and 6 has been required and at least one jet with only one charged particle. The invariant mass of both jets had to be less than 3 GeV/c^2.

The leading track of each jet, defined as the particle with the highest momenta, has been required to lie in the polar angle range $\mid cos\theta_l \mid < 0.98$. In order to reject events where the jets are back to back, and radiative return events with a photon along the beam pipe, the acoplanarity has been required to be less than 13° if both leading tracks are in the barrel region (25° in other case). In addition E_t was required to be greater than $0.08 \cdot \sqrt{s}$ $(0.1 \cdot \sqrt{s})$ and $P_t > 0.04 \cdot \sqrt{s}$, being E_t and P_t the transverse momentum scalar and vectorial to the beam direction.

Final cuts are used to reduce the remaining background. The energy detected within a cone of 30° around the beam axis had to be less than $0.1 \cdot \sqrt{s}$ and the acollinearity less than 150°.

If a tau decay candidate particle has not been identified as either a muon or an electron, it has been considered as a hadron. In order to use the τ polarisation as discriminating variable the τ hadronic decays have been further classified into four categories: π, $\pi + n\gamma$, 3π and others.

After this selection W^+W^- pair-production is the dominant background, around 80%, mostly $\tau^+\nu_\tau\tau^-\overline{\nu}_\tau$ events. Events from both H^+H^- signal and this W^+W^- background have similar topologies and it is not possible to reconstruct the boson mass due to the presence of missing neutrinos in the decay of each of the bosons. Two important differences have been used in order to discriminate the signal and this WW background: the boson polar angle and the τ polarisation.

Assuming that ν_τ has a definite helicity, then the polarisation of τ leptons originating from heavy bosons decays is determined entirely by the properties of weak interactions and the nature of the parent boson. The helicity configuration is $H^- \rightarrow {\tau^-}_R {\nu_\tau}_R$ $(H^+ \rightarrow {\tau^+}_L {\overline{\nu}_\tau}_L)$ and in the case of $W^\pm$ bosons is $W^- \rightarrow {\tau^-}_L {\nu_\tau}_R$ $(W^+ \rightarrow {\tau^+}_R {\overline{\nu}_\tau}_L)$, consequently, ${P_\tau}^H = +1$ and ${P_\tau}^W = -1$. The angular and momentum distributions depend on polarisation, therefore it is possible to build estimators of the τ polarisation to discriminate between the two contributions.

The information on the τ polarisation is extracted from the observed kinematic distributions of its decays products, e.g. angles and momentum. The estimators are equivalent to those used at LEP1 [16] as for charged Higgs bosons masses close to the threshold the boost of the bosons is relatively small and the τ energy is similar (40-50 GeV).

A likelihood to separate the signal from the background has been built using four 'independent' variables: the estimators of the τ polarisation and the boson polar angle of both τ's.

The likelihood function has been defined as follows. For each of the N discriminating variables, the fractions $F_i^{HH}(x_i)$ and $F_i^{bkg}(x_i)$ of respectively H$^+$H$^-$ and background events corresponding to a given value x_i of the i^{th} variable, have been extracted from a sample of simulated background and H$^+$H$^-$ events with equal populations. The signal likelihood has been computed as the normalised product of these individual fractions, $\prod_{i=1,N} F_i^{HH}(x_i)/(\prod_{i=1,N} F_i^{HH}(x_i) + \prod_{i=1,N} F_i^{bkg}(x_i))$.

The number of real data events, expected backgrounds and the signal efficiency after each set of cuts adopted in the analysis are given in Table 1 for the highest energy sample. The distributions of the final discriminating variable for the data and simulated signal and backgrounds at 189 GeV are shown in Fig 1.

Table 1: *Number of selected events and signal efficiency in the leptonic channel at different stages of the event selection for $\sqrt{s}$ = 189 GeV.*

selection	data	Total Bkg.	W^+W^- Bkg.	Rest Bkg.	Efficiency H^+H^- (%) ($M_H = 75 GeV/c^2$)
τ selection	11772	11193	21	11172	52.2
Angle cuts	593	513	17	496	43.4
Missing energy cuts	19	19.3	15.0	4.3	36.7
Final cuts	15	15.8	13.1	2.7	33.7

2.2 The hadronic channel

In the fully hadronic decay channel, each charged Higgs is expected to decay into a $c\bar{s}$ pair, producing a four jet final state. The two sources of background in this channel are the $q\bar{q}gg$ QCD background and fully hadronic four fermion final states. As the significance of the Z^0Z^0 pairs for the analysis is negligible compared to the W^+W^- pairs, the four fermion sample is referred to as W^+W^- in the rest of the paper. The data collected by DELPHI at centre-of-mass energies of 183 GeV and 189 GeV with corresponding integrated luminosities of 53.5 pb^{-1} and 158.0 pb^{-1} have been analysed.

Events have been clustered into four jets using the Durham algorithm [5]. The particle quality requirements and the first level hadronic four jet event selection followed in this analysis have been the same as for the DELPHI neutral Higgs analysis [8].

In order to reject more effectively three jet like QCD background events a cut on the Durham clustering parameter y_{34} value for transition from three to four jets has been required to be greater than 0.003. As the probability for ambiguities in forcing to four jets is higher in multi-jet like events, the y_{45} value for transition from four to five jets was required to be smaller than 0.010.

Energy-momentum conservation has been imposed by performing a 4-C fit on these events and the difference between the two di-jet masses for each jet pairing has been computed. A 5-C fit, assuming equal boson masses, has been applied in order to improve the resolution on the di-jet mass M_{jj}. The di-jet combination giving the smallest χ^2 has been selected for the mass reconstruction. Events for which the χ^2 per degrees of freedom of this combination exceeded 3 or the difference of the masses computed after the 4-C fit exceeded 8 GeV/c^2 have been rejected.

The major contribution of the W^+W^- events with reconstructed mass below 75 GeV/c^2 is due to wrong di-jet pairing. These wrongly paired events are characterised by larger difference between the masses of the two di-jets, i.e. the two boson candidates. As the true quark-antiquarks pairs are connected by a QCD colour field, in which the hadrons are produced in the fragmentation process, the wrongly paired events can also be identified using a method of colour connection reconstruction [9].

The colour connection reconstruction is based on the fact that in the rest frame of the correct quark antiquark pair the hadrons that are produced in this colour string should have vanishing transverse momenta relative to the quark antiquark pair axis. This could be distorted by hard gluon emission but these events are suppressed with the y_{45} Durham parameter cut. In the rest frame of wrong quark pairs the hadrons are boosted into an artificial Lorenz frame and their transverse momenta relative to the quark quark axis are larger. The correct pairing is found by calculating the sum of transverse particle momenta in each of the three possible pairing hypotheses and choosing the one with smallest sum. The pairing chosen using the colour connection reconstruction is compared to the pairing chosen using the minimisation of χ^2 of the 5-C kinematical fit. The output of this comparison, p_t-veto, is binary information: agreement or disagreement.

Also the production polar angle of the positively charged boson discriminates between W^+W^- and Higgs pairs. This angle is reconstructed as the polar angle of the di-jet with higher charge. The distribution of this variable allows the discrimination of the signal against the wrongly paired W^+W^- events and QCD events even though in these cases it is not the true boson production angle.

The charged Higgs boson is expected to couple predominantly to $c\bar{s}$ in its hadronic decay mode. Therefore the QCD and W^+W^- backgrounds can be partially suppressed by selecting final states consistent with being $c\bar{s}\bar{c}s$. A flavour tagging algorithm has been developed for the study of multiparton final states [10]. This tagging is based on nine discriminating variables: three of them are related to the identified lepton and hadron content of the jet, two depend on kinematical variables and four on the reconstructed secondary decay structure. The finite c lifetime is exploited to distinguish between c and light quark jets, while the c mass and decay multiplicity, was used to discriminate against b jets. Furthermore s and c jets can be distinguished from u and d jets by the presence of an identified energetic kaon. A likelihood variable was computed using the individual jet variables as discussed below for the anti-WW function. The responses for the individual jets have been further combined into an event $c\bar{s}\bar{c}s$ probability.

The four variables described above: di-jet pair mass difference, di-jet momentum polar angle, event $cscs$ probability and the p_t-veto, have been combined to form an event anti-WW likelihood function (defined as in the leptonic channel) separating W^+W^- events from H^+H^- events. The response of this likelihood discriminates H^+H^- also from the QCD background events.

QCD background events differ also kinematically from pair-produced bosons [11]. In order to reject the QCD background more effectively the following additional variables have been used: the product of the minimum jet energy and the minimum di-jet angle $\mathrm{Min}(E_{jet}) \cdot \min(\alpha_{jets})$ and the event acoplanarity.

The number of real data events, expected backgrounds and the signal efficiency after each of the set of cuts adopted in the analysis are given in Table 2 for the highest energy sample. The distributions of the WW and QCD discriminating variables and the mass spectra for the data and simulated signal and backgrounds are shown in Fig 2 and Fig 3.

2.3 The mixed channel

In this channel one of the charged Higgs bosons decays into a $c\bar{s}$ quark pair, while the other decays into $\tau\nu$. Such an event is characterised by two hadronic jets, a τ candidate and missing energy carried by the neutrinos. The dominating background processes are QCD $q\bar{q}\gamma$ events and semileptonic decays of W^+W^-. The data collected by DELPHI at centre-of-mass energies of 183 GeV and 189 GeV with corresponding integrated luminosities of 53.5 pb^{-1} and 158.0 pb^{-1} have been analysed.

The particle quality requirements and event preselection have been the same as in the previous DELPHI analysis described in [18]. One additional cut has been applied requiring the event thrust value to be below 0.95. Events have been clustered into three jets using the Durham algorithm. The jet with the smallest charged particle multiplicity has been treated as the τ candidate and if more than one of the jets have the same number of charged particles, the one with smallest energy has been chosen. As in the leptonic channel analysis, the τ candidate has been classified according to its decay mode into the following classes: electron, μ, $\pi, \pi + n\gamma, 3\pi$ and others. The τ candidate jet has been required to have an invariant mass below 3 GeV/c^2. Electron has to have momentum below 0.13 $\sqrt{s}$ and electromagnetic energy below 0.14 $\sqrt{s}$. For muons the momentum has to be below 0.13 $\sqrt{s}$.

The mass of the decaying bosons M_{jj} has been reconstructed using a constrained fit requiring energy and momentum conservation and equal masses of the two bosons. The three components of the momentum vector of the ν_τ from the W and the magnitude of the τ momentum have been treated as free parameters, reducing the number of degrees of freedom in the fit from 5 to 1. Only events with mass in the range 48 GeV/c^2 $< M_{jj} <$ 78 GeV/c^2 have been further considered in the analysis.

Separate likelihood functions have been defined to distinguish the signal events from the QCD background and from the W^+W^- background, similarly to the case of the leptonic channel described above. The polar angle of the total momentum, the logarithm of the clustering distance, defined as the y_{cut} value in the Durham algorithm for which the number of jets changes from two to three, the product of the minimum jet energy and the minimum angle between two jets and, finally, a function of the cs probability of the hadronic di-jet, have been used as discriminating variables to define the event anti-QCD likelihood.

For the event anti-WW likelihood the variables used include the reconstructed polar

Table 2: *Number of selected events and signal efficiency in the hadronic final state at different stages of the event selection procedure for $\sqrt{s}$ = 189 GeV.*

Selection	Data	Total Bkg	W^+W^- Bkg	QCD Bkg	Efficiency H^+H^- (%) (M_H=70 GeV/c^2)
Event preselection	1758	1708	1124	584	85.3
Durham y_{cut}	1331	1298	946	352	73.3
χ^2 Cut	857	856	675	181	54.1
ΔM Cut	463	477	398	79	39.0
Likelihood cuts	145	141	130	11	18.8

angle of the negatively charged boson (where the charge has been taken to be that of the leading charged particle from the τ jet), the angle between the W boson and the τ in the W rest frame, the τ polarisation estimator (different for each decay channel as in the leptonic analysis) and the cs probability of the hadronic di-jet (defined for the di-jet as for the whole event in the hadronic analysis).

The number of real data events, expected backgrounds and the signal efficiency after each of the set of cuts adopted in the analysis are given in Table 3 for the highest energy sample. The distributions of the WW and QCD discriminating variables and the mass spectra for the data and simulated signal and backgrounds are shown in Fig 4 and Fig 5.

Table 3: *Number of selected events and signal efficiency in the semi-leptonic final state at different stages of the event selection procedure for $\sqrt{s}$ = 189 GeV.*

Selection	Data	Total Bkg	4 fermion Bkg	2 fermion Bkg	Efficiency H^+H^- (%) (M_H=70 GeV/c^2)
Event Preselection	2526	2299	1363	922	80
τ selection	830	731	380	344	57
$48 < M_{jj} < 78$	363	312	129	179	43
Likelihood cuts	55	55.9	45.6	9.5	32

3 Results

The number of real data and background events and the estimated efficiencies for these selections for different $H^\pm$ masses are summarised in Table 4 for the three final states.

Table 4: *Number of events, expected background and signal efficiencies for different charged Higgs masses in the hadronic, semileptonic and leptonic channels.*

$\sqrt{s}$	Channel	Data	Expected Bkg.	Eff. M_H = 60 GeV/c^2	Eff. M_H = 65 GeV/c^2	Eff. M_H = 70 GeV/c^2	Eff. M_H = 75 GeV/c^2
183	$cscs$	50	45.3	22.4	19.5	16.3	12.8
189	$cscs$	145	141.1	21.2	20.0	18.8	17.4
183	$cs\tau\nu$	18	24.4	39.2	37.5	34.0	28.7
189	$cs\tau\nu$	55	55.9	37.0	35.7	31.9	25.3
183	$\tau\nu\tau\nu$	5	4.8	32.6	33.6	32.9	33.5
189	$\tau\nu\tau\nu$	15	15.8	30.9	31.9	33.1	33.7

3.1 Determination of the Mass Limit

No excess of events compared to the expected backgrounds has been observed in any of the three different final states investigated. A lower limit for a charged Higgs boson mass has been derived at 95% confidence level as a function of the hadronic Higgs decay branching ratio BR(H $\rightarrow$ *hadrons*). The confidence in the signal hypothesis, CL_s, has been calculated using a likelihood ratio technique [17].

The background and signal probability density functions of one or two discriminating variables in each channel have been used. In the hadronic and semi-leptonic channels the two discriminating variables have been the reconstructed mass and the anti-WW likelihood while in the leptonic channel only one background discrimination likelihood has been used because mass reconstruction is not possible. The distributions for the discriminating variable of signal events, obtained by the simulation at different $\mathrm{H}^{\pm}$ mass values for each $\sqrt{s}$, have been interpolated for intermediate mass values. The signal efficiencies have been fitted with polynomial functions, to obtain the expected signal rate at any given mass.

Uncertainties in the expected background and in the signal efficiency have been accounted for. These uncertainties are due both to the finite simulation statistics available and to possible differences in the response of the selection variables in data and simulation. The background events in simulation have been reweighted such that each variable exactly agreed in shape with that of the real data and the background has been recomputed. The overall background uncertainty has been obtained by summing in quadrature the differences in the background estimates, after changing each of the variables, and the statistical error. A Gaussian smearing of the central values of the number of expected background events by their estimated uncertainties has been introduced in the limit derivation program. The uncertainties on the signal efficiencies are dominated by their statistical errors and have been also accounted for.

The results are summarised in Figure 6. Independently of the hadronic decay branching ratio a lower $\mathrm{H}^{\pm}$ mass limit of $M_{\mathrm{H}^{\pm}} > 66.9$ GeV/c^2 can be set at 95% confidence level. For fully leptonic decays of the charged Higgs boson this limit becomes $M_{\mathrm{H}^{\pm}} >$ 78.5 GeV/c^2.

4 Conclusion

A search for pair-produced charged Higgs bosons has been performed using the full statistics collected by DELPHI at LEP at centre-of-mass energies of 183 GeV and 189 GeV analysing the $\tau\nu\tau\nu$, $c\bar{s}\tau\nu$ and $c\bar{s}\bar{c}s$ final states. No significant excess of candidates has been observed and a lower limit on the charged Higgs mass of 66.9 GeV/c^2 has been set at 95% confidence level.

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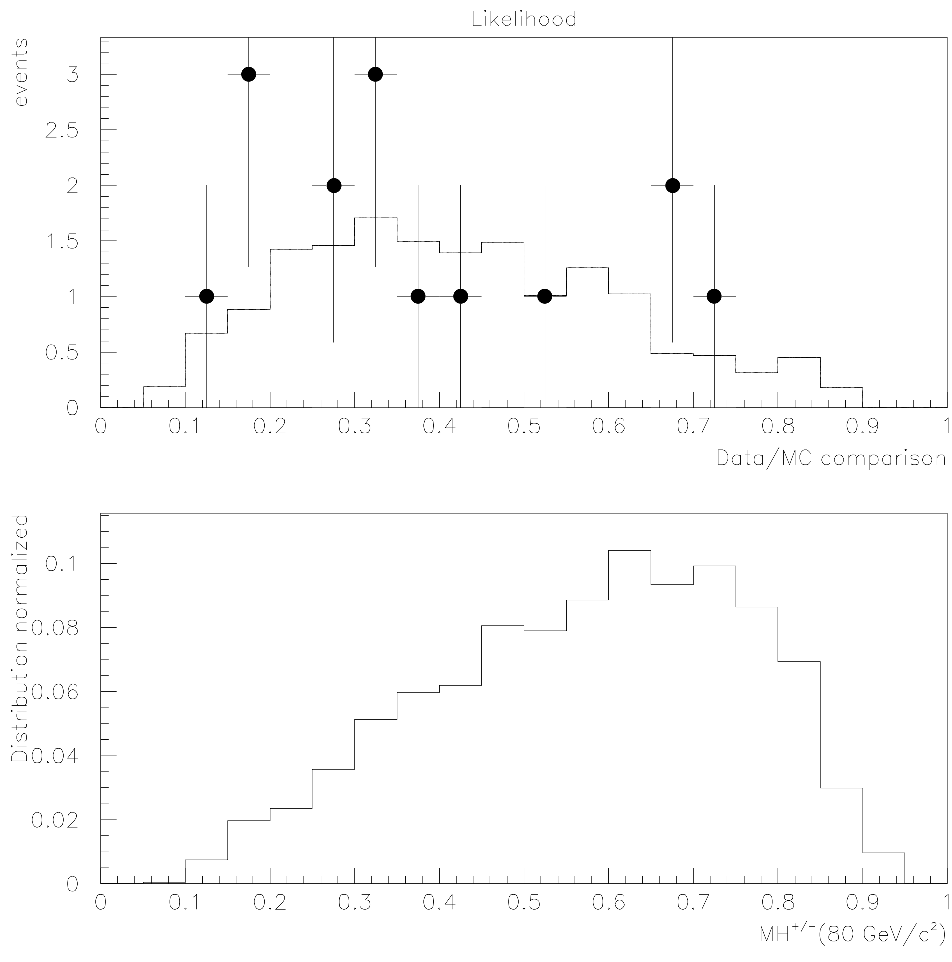

Figure 1: *Distributions of the background separating likelihood for leptonic events at 189 GeV at the final selection level. The background and data are presented in the upper plot and the 80 GeV/c^2 signal in the lower plot.*

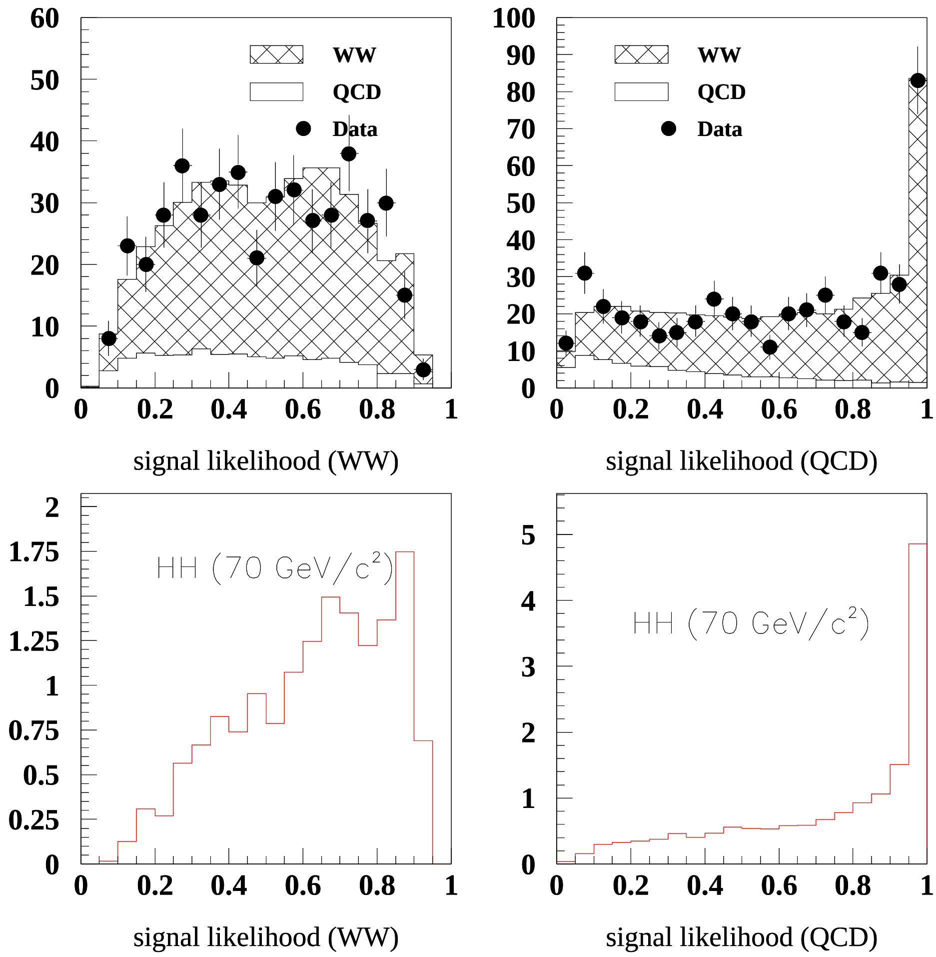

Figure 2: *Distributions of the WW and QCD separating likelihoods for hadronic events at 189 GeV at the final selection level. The backgrounds and data are presented in the upper plots and the 70 GeV/c^2 signal in the lower plots.*

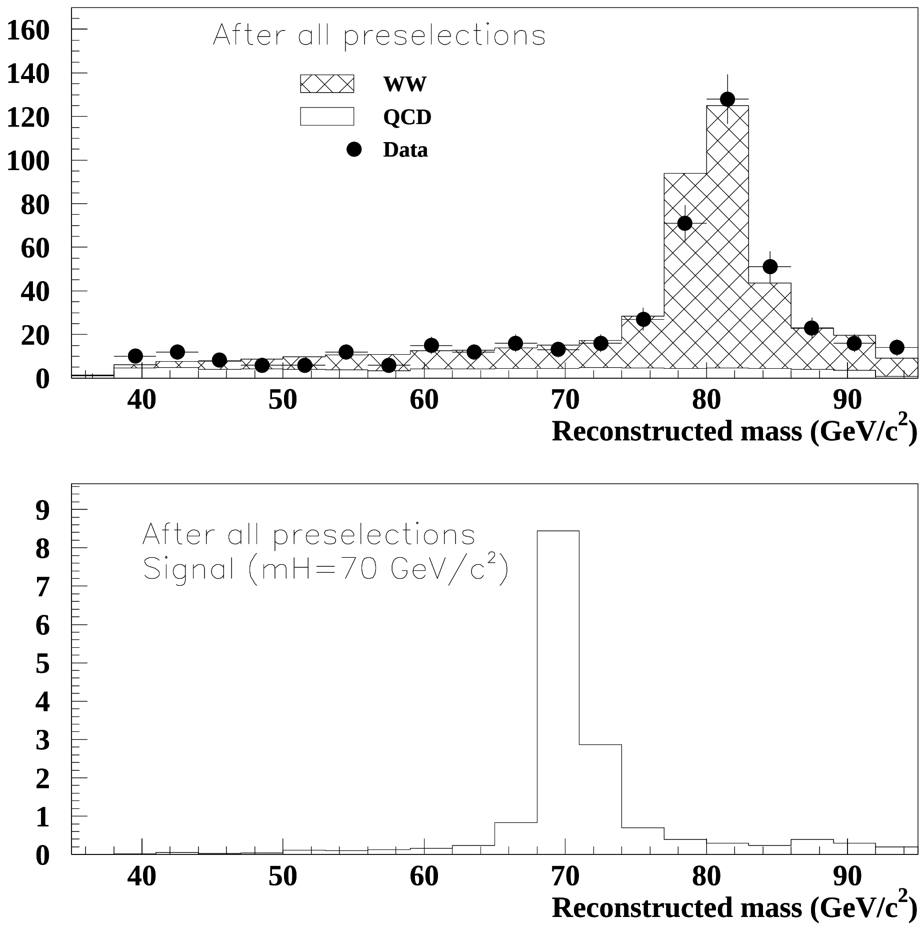

Figure 3: *Reconstructed mass distribution of hadronic events at 189 GeV at the final selection level. The backgrounds and data are presented in the upper plot and the 70 GeV/c^2 signal in the lower plot.*

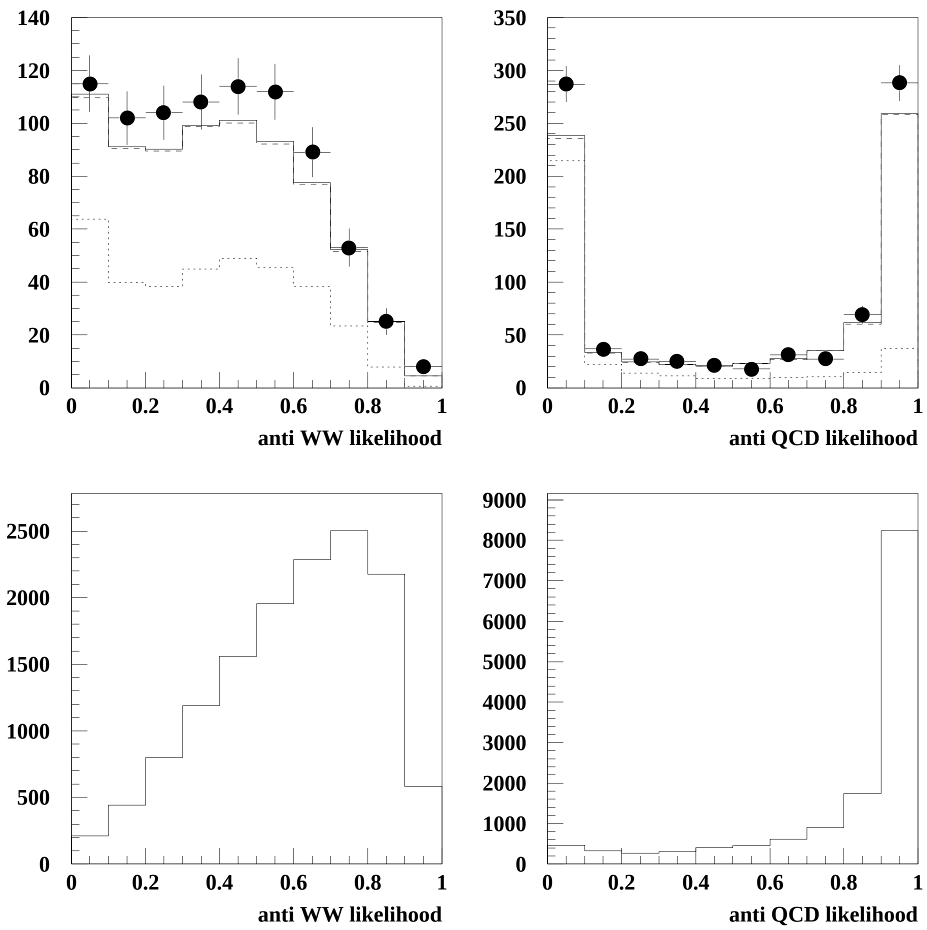

Figure 4: *Distributions of the WW and QCD separating likelihoods for mixed channel events at 189 GeV at the final selection level. The backgrounds and data are presented in the upper plots (the dashed histograms stand for QCD background and the solid ones for four-fermion background) and the 70 GeV/c^2 signal in the lower plots.*

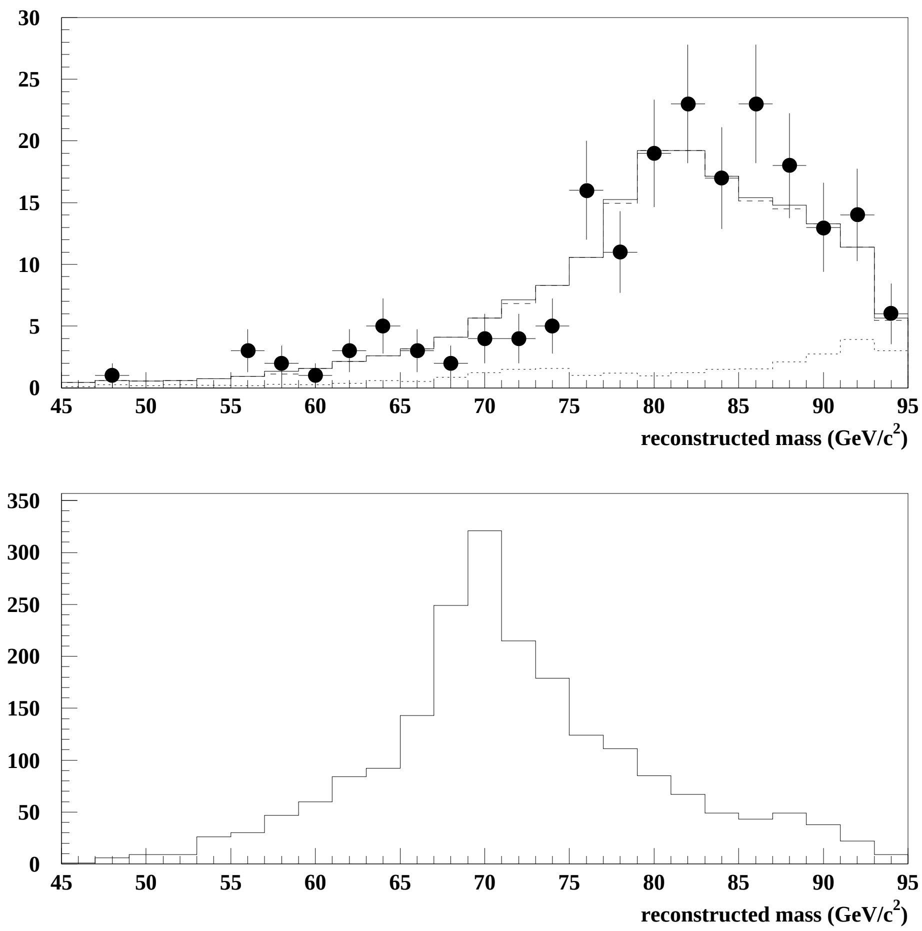

Figure 5: *Reconstructed mass distribution of mixed channel events at 189 GeV at the final selection level. The backgrounds and data are presented in the upper plot (the dashed histogram stands for QCD background and the solid one for four-fermion background) and the 70 GeV/c^2 signal in the lower plot.*

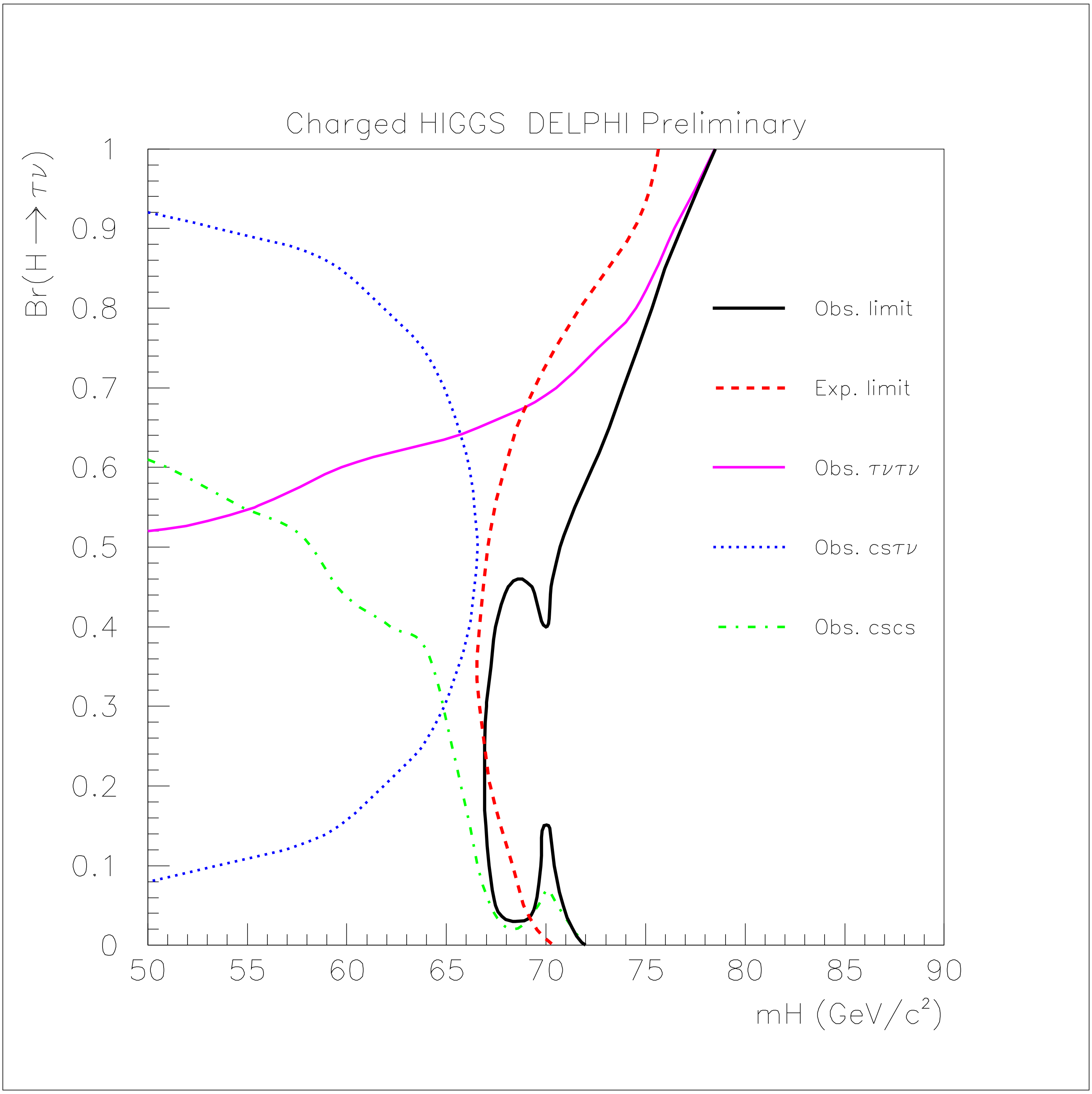

Figure 6: *The 95% confidence level observed and expected exclusion regions for $H^{\pm}$ in the plane BR($H \to$ hadrons) vs. $M_{H^{\pm}}$ obtained from a combination of the search results in the hadronic, semileptonic and fully leptonic decay channels at $\sqrt{s}$ = 183 GeV and 189 GeV.*