Search for the charged Higgs boson in Z^0 decay

L3 Collaboration

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We have searched for the pair produced charged Higgs particles in the decays of Z^0 for the decay channels of $H^+H^-\to\tau^+\nu\tau^-\bar{\nu}$, $H^+H^-\to\tau\nu cs$ and $H^+H^-\to c\bar{s}\bar{c}s$. The data sample analyzed corresponds to approximately 50 000 hadronic decays of Z^0. A lower limit of 36.5 GeV is obtained at the 95% confidence level for the mass of charged Higgs particle, independent of its decay branching ratio.

1. Introduction

The standard model [1] has been very successful in describing experimental data from electroweak interactions. This has been thoroughly demonstrated by recent experimental data on the properties of the Z^0 boson at the LEP collider [2]. However, another important aspect of the theory, the Higgs mechanism, has not yet been experimentally verified.

The standard model requires one complex scalar doublet to generate Z^0 and $W^\pm$ boson masses, though the framework of the theory does not restrict the number of doublets to one. Indeed, several theoretical models with two or more Higgs doublets have been proposed to give alternative theoretical solutions to the electroweak *CP* violation [3], the suppression of *CP* violation in strong interactions [4], and the $B^0\bar{B}^0$ mixing [5]. Moreover, a non-minimal Higgs structure is required by many of the new theoretical frameworks aiming at solving the difficulties of the standard model [6], most notably by the supersymmetric extension of the standard model [7].

In this paper we consider the minimal extension of the standard model with two complex Higgs doublets. In this model, the spontaneous breaking of the gauge symmetry leaves five physical Higgs particles, of which two are charged (H^+, H^-). The mass of the charged Higgs is not constrained by the theory, and they could be pair produced by Z^0 decay.

The partial width of Z^0 for the charged Higgs is [8]

$$\Gamma(Z^0\to H^+H^-)=\frac{G_F M_Z^3}{6\sqrt{2}\,\pi}\left(\tfrac{1}{2}-\sin^2\theta_W\right)^2\beta_H^3,$$

where $\beta_H=\sqrt{1-4M_H^2/M_Z^2}$.

The charged Higgs is expected to decay preferentially to the heaviest fermion pairs. In the leptonic

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channel, the decay into τ and ν dominates. In the hadronic channel, the decay into c and b quark is suppressed compared to the c and s quark due to the small value of the quark mixing parameter $|V_{cb}|$.

In this paper, we use the following three processes to search for $H^{\pm}$:

$$Z^0 \to H^+H^- \to (\tau^+\nu\tau^-\bar{\nu}),\ (\tau\nu cs) \text{ and } (c\bar{s}\bar{c}s).$$

As the exact branching ratios into these channels are model dependent [8], in the following analysis we present our results as a function of $Br(H^{\pm}\to\tau\nu)$, the branching ratio of charged Higgs into tau and neutrino.

This analysis has been performed using the data collected during an energy scan around the Z^0 peak in March–June 1990. In this period, approximately 50 000 hadronic Z^0 decays have been collected and they are used here for normalization. The previous mass limits of $H^{\pm}$ obtained from other experiments at e^+e^- colliders can be found in ref. [9].

2. The L3 detector

The L3 detector covers 99% of 4π with calorimetry. The detector consists of a central vertex chamber, a high resolution electromagnetic calorimeter composed of BGO crystals, a ring of scintillation counters, a uranium and brass hadron calorimeter with proportional wire chamber readout, and a high precision muon chamber system. These detectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 T along the beam axis. The detector and its performance are described in detail elsewhere [10].

3. Search for H^+H^- decaying into $\tau^+\nu\tau^-\bar{\nu}$

$Z^0\to H^+H^-\to\tau^+\nu\tau^-\bar{\nu}$ events are identified requiring one τ decaying into a muon and another τ decaying into a low multiplicity jet. In order to select those events and suppress the background coming from $Z^0\to\tau^+\tau^-(\gamma)$ events, the following cuts have been applied:

(1) We require at least one reconstructed muon in the detector fulfilling the following criteria:

(i) $|\cos\theta_\mu|<0.7$, where θ_μ is the polar angle of the muon track;

(ii) the reconstructed muon momentum should be greater than 3 GeV and less than 35 GeV;

(iii) there should be less than two calorimetric clusters around the muon track within a cone of 30° half angle.

(2) If the muon track has an associated scintillator hit, the time of the hit should be within ±3 ns of the beam crossing after correcting for the time of flight.

(3) There should be less than eight clusters in the event besides those associated with the muon.

(4) There should be one (and only one) jet with energy greater than 4 GeV associated with charged tracks, and forming an angle with the muon in the range of $30°<\theta_{jet,\mu}<168°$. Fig. 1 shows the distribution of this angle for the data and the Higgs Monte Carlo after all other cuts have been applied.

Applying these cuts to Monte Carlo generated events, we computed a detection efficiency for $Z^0\to H^+H^-\to\tau^+\nu\tau^-\bar{\nu}$ events of about 9% in the range $20<M_H<40$ GeV.

No events have been found in the data. The mass limit from this analysis as a function of $Br(H^{\pm}\to\tau\nu)$ is shown in fig. 4 by the contour A. In obtaining the limit, we have reduced the number of expected events

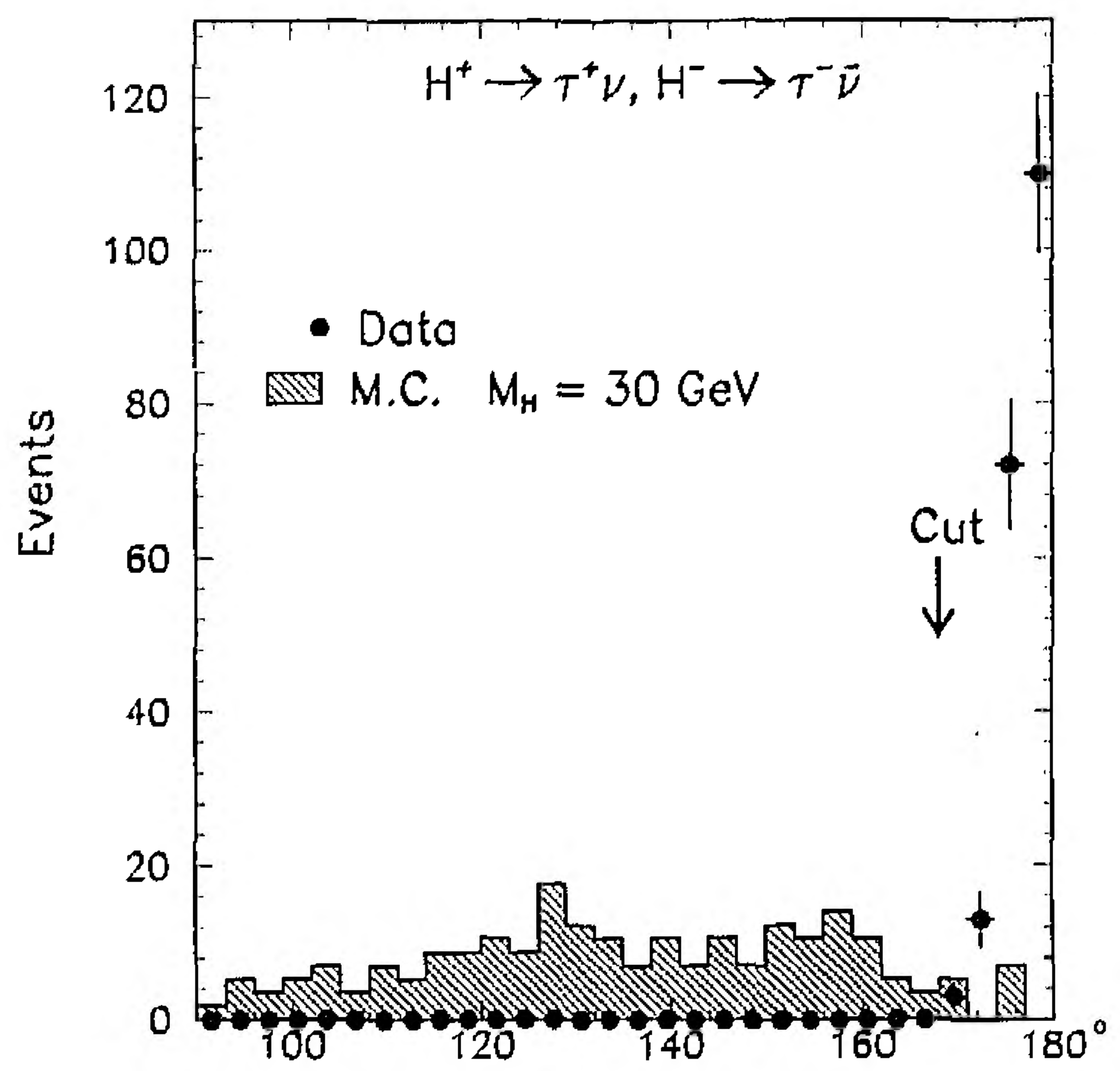

Fig. 1. The distribution of the angle between the muon and the jet, $\theta_{jet,\mu}$, after applying all other cuts to select the $H^+H^-\to\tau^+\nu\tau^-\bar{\nu}$ event. The filled circles are from data and the shaded histogram is from the H^+H^- Monte Carlo of $M_H=30$ GeV. For the purpose of presentation, the Monte Carlo is normalized to the data for the same number of Z^0 decays with $Br(H^{\pm}\to\tau\nu)=100\%$.

by 10% to take into account the systematic error of the expected number of events mainly due to the uncertainty of the acceptance.

4. Search for H^+H^- decaying into τνcs

$Z^0 \to H^+H^- \to \tau\nu cs$ events are identified by requiring the τ decaying into a muon and the c and s quark hadronizing into one or two jets.

In addition to the muon selected by the same cuts described above, we require the following conditions of the hadronic system:

(1) The total energy of the event should be less than 60 GeV.

(2) There should be at least four calorimetric clusters in the event besides those associated with the muon.

(3) There should be at least one jet with energy greater than 4 GeV associated with charged tracks. The nearest jet to the muon should have an angle in the range of $30° < \theta_{\mathrm{jet},\mu} < 164°$. Fig. 2 shows the distribution of this angle for the data and the Higgs Monte Carlo after all other cuts have been applied.

The acceptance of $Z^0 \to H^+H^- \to \tau\nu cs$ event was calculated by applying the above cuts on the Monte Carlo generated events. For the hadronization of c and s quarks, we used the program JETSET 7.2 [11] with $\Lambda_{LL} = 290$ MeV and string fragmentation. We found a detection efficiency of about 11% in the range of $20 < M_H < 40$ GeV.

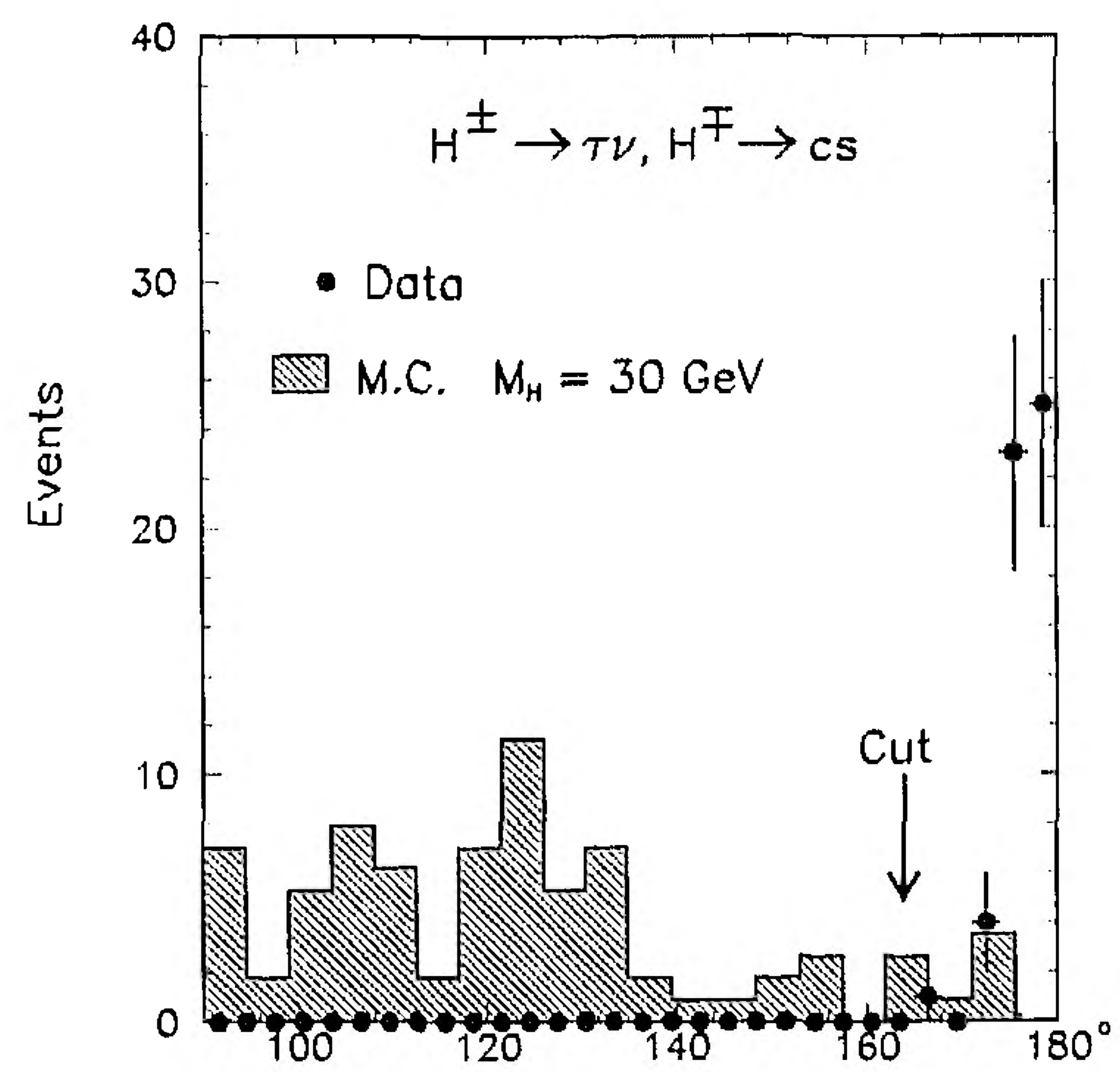

Fig. 2. The distribution of the angle between the muon and the nearest jet, $\theta_{\mathrm{jet},\mu}$, after applying all other cuts to select the $H^+H^- \to \tau\nu cs$ event. The filled circles are from data and the shaded histogram is from the H^+H^- Monte Carlo of $M_H = 30$ GeV. For the purpose of presentation, the Monte Carlo is normalized to the data for the same number of Z^0 decays with $\mathrm{Br}(H^{\pm} \to \tau\nu) = 50\%$.

No events have been found in the data. The mass limit of $H^{\pm}$ from this analysis as a function of $\mathrm{Br}(H^{\pm} \to \tau\nu)$ is given in fig. 4 by the contour B. The systematic error of 10% is included in the limit as in the analysis above.

5. Search for H^+H^- decaying into $c\bar{s}\bar{c}s$

The search for $H^+H^- \to c\bar{s}\bar{c}s$ was performed by analyzing the hadronic events from Z^0 selected by the standard hadron cuts [12]. Each hadronic event is classified into a multi-jet event by using the "JADE" version of the jet recombination algorithm [13]. In this scheme, we first calculate the scaled invariant mass squared

$$y_{ij} = 2E_iE_j/E_{\mathrm{vis}}^2 \cdot (1 - \cos\vartheta_{ij})$$

for each pair of the energy clusters in the event, where E_i, E_j are the energies of the clusters, E_{vis} is the total energy observed and ϑ_{ij} is the opening angle between clusters i and j. The cluster pair for which y_{ij} is the smallest is then replaced by a pseudo-cluster k with four-momentum $p_k = p_i + p_j$. The procedure is repeated until all the values of y_{ij} in the event exceed the jet resolution parameter y_{cut}. The remaining (pseudo)clusters are called jets.

The Higgs event sample consists of exactly four jet events with $y_{\mathrm{cut}} = 0.02$, where this value of y_{cut} corresponds to the minimum jet pair mass of 13 GeV in the event. Approximately 4 200 four-jet events have been obtained from a total of ≈ 50 000 hadronic decays from Z^0.

Four jets were further combined into two pairs of jets, (i, j) and (k, l), by taking the combination which has the smallest difference between two invariant masses. This procedure is to identify the proper pairs of jets originating from the decay of two Higgs particles.

The event candidates were then selected by applying the following cuts which are independent of the Higgs mass in search:

(1) $(E_i+E_j-\sqrt{s/2})^2+(E_k+E_l-\sqrt{s/2})^2<16$ GeV ^{2} and $|\cos\vartheta_{ij}-\cos\vartheta_{kl}|<0.3$.

(2) The polar angle of the thrust axis should be in the range of $60°<\vartheta_{\mathrm{thrust}}<120°$. This cut is to enrich the Higgs sample by taking into account the $\sin^2\vartheta$ distribution of the H^+H^- production as opposed to the $1+\cos^2\vartheta$ distribution of the QCD background.

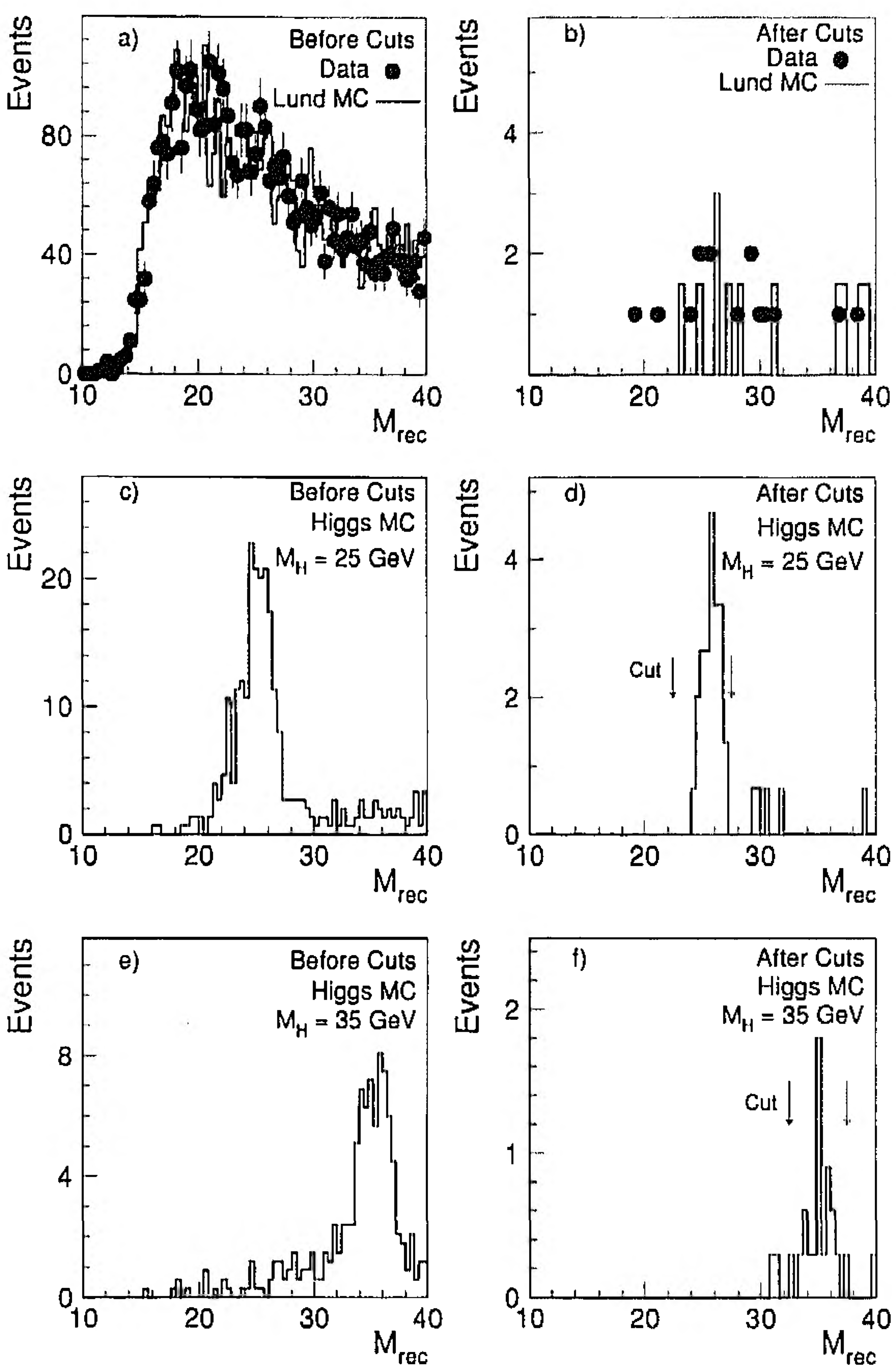

Fig. 3. The distribution of the reconstructed Higgs mass, M_{rec}, obtained from hadronic four-jet events for (a) data (filled circles) and QCD Monte Carlo (histogram) before cuts. (b) data (filled circles) and QCD Monte Carlo (histogram) after all other cuts besides M_{rec} cut. For (a) and (b), the Monte Carlo is normalized to the same number of four-jet events before cuts. (c) H^+H^- Monte Carlo of $M_H=25$ GeV before cuts. (d) H^+H^- Monte Carlo of $M_H=25$ GeV after all other cuts. The cut on M_{rec} is indicated in the figure. For the purpose of presentation, the H^+H^- Monte Carlo is normalized to the data for the same number of Z^0 decays with $\mathrm{Br}(H^\pm\to cs)=100\%$. (e) and (f) are the same as (c) and (d) respectively but with $M_H=35$ GeV.

(3) The lowest energy jet should have at least 12 GeV. This is to remove preferentially QCD events with gluon radiation.

For each Higgs mass regions, we then required:

(4) The thrust T of the event should be $T_{\mathrm{low}}<T<T_{\mathrm{high}}$, where the threshold values T_{low} and T_{high} were optimized for the best signal-to-noise ratio depending on the Higgs mass M_H.

(5) $|M_{\mathrm{rec}}-M_H|<2.5$ GeV where M_{rec} is the average of two invariant masses reconstructed from the jet pair (i, j) and (k, l). The value of 2.5 GeV corresponds approximately 1.5 times the resolution of M_{rec}. The distributions of M_{rec} are shown in fig. 3 for the data and Monte Carlo of $M_H=25$ and 35 GeV.

The number of observed $H^+H^-\to c\bar{s}\bar{c}s$ candidates from hadron data, typically three events, is consistent with the expectation from the QCD background. The acceptance ε of $H^+H^-\to c\bar{s}\bar{c}s$ event has been calculated by applying the above cuts on the Monte Carlo generated events. We found $\varepsilon\simeq 3\%$ at $M_H=37$ GeV and $\varepsilon\simeq 5\%$ at $M_H=20$ GeV. The systematic uncertainty of the acceptance is estimated to be 12% including the Monte Carlo statistics.

The limit of the Higgs mass is derived as a function of $\mathrm{Br}(H^\pm\to cs)$ by applying a Poisson statistics between the observed number of candidates and the expected number of signal and background events cal-

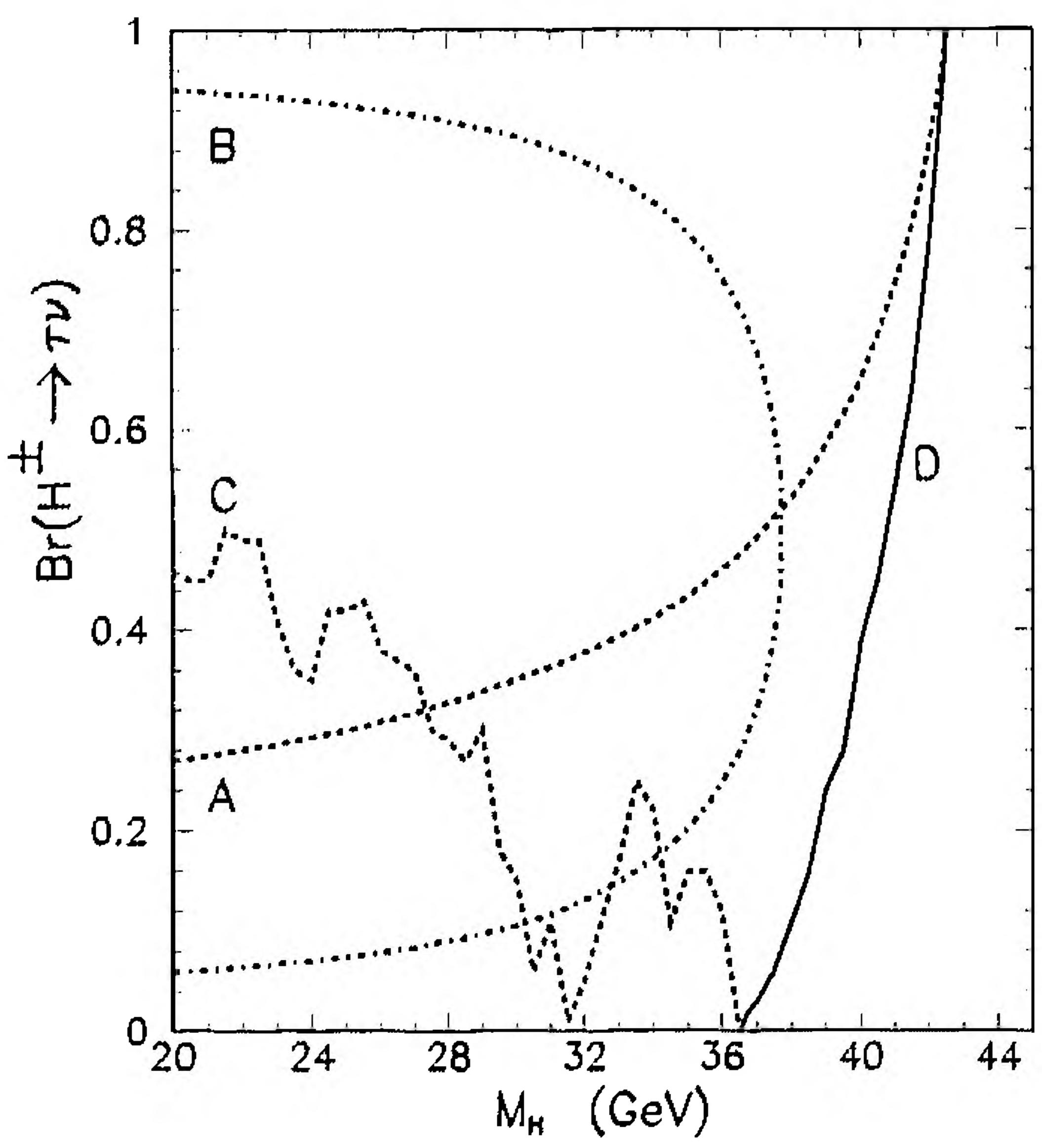

Fig. 4. The excluded regions of the charged Higgs mass as a function of $\mathrm{Br}(H^\pm\to\tau\nu)$ by analyzing $H^+H^-\to\tau^+\nu\tau^-\bar{\nu}$ (contour A), $H^+H^-\to\tau\nu cs$ (contour B) and $H^+H^-\to c\bar{s}\bar{c}s$ (contour C). The contour D shows a combined limit of all three decay channels.

culated by the Monte Carlo [14]. To take into account the systematic error, we reduced the number of expected events by 12%. The excluded region of the Higgs mass by this analysis is shown as the contour C in fig. 4 as a function of $Br(H^{\pm}\to\tau\nu)\equiv 1-Br(H^{\pm}\to cs)$.

6. Conclusions

We have searched for the pair produced charged Higgs particles in the decays of the Z^0 for the decay channels of $H^+H^-\to\tau^+\nu\tau^-\bar{\nu}$, $H^+H^-\to\tau\nu cs$ and $H^+H^-\to c\bar{s}\bar{c}s$. No indication of the H^+H^- production was observed. The excluded region of the charged Higgs mass obtained by combining all three decay channels is shown as the contour D in fig. 4 as a function of $Br(H^{\pm}\to\tau\nu)$. The Monte Carlo study showed that the acceptance of the event with $H^{\pm}\to cb$ decay is the same as the $H^{\pm}\to cs$ within the statistics.

A lower limit of 36.5 GeV is obtained at the 95% confidence level for the charged Higgs mass, independent of the branching ratio of the Higgs into leptons or hadrons.

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