SEARCH FOR CHARGED HIGGS AND TECHNIPIONS AT PETRA

TASSO Collaboration

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We have searched for hadronic decay modes of unstable pointlike charged spin-zero particles such as charged Higgs bosons or technipions, produced in pairs in e^+e^- annihilation. Together with previous results on leptonic decay modes from other experiments, we conclude that at the 95% confidence level such particles do not exist in the mass range of 5 to 13 GeV.

It is of fundamental importance to search for pointlike charged scalar particles, including in particular charged Higgs [1] and technipions [2]. In current theories of weak interactions, spin-zero particles are needed in order to generate masses for the intermediate vector bosons W and Z^0. In the original Higgs mechanism used in the Weinberg–Salam theory [3], the spin-zero particle is elementary and has no charged partner. If there are charged partners, these charged Higgs [1] can be pair produced in e^+e^- annihilation and, similar to the neutral Higgs, decay predominantly into the heaviest quarks and leptons that are kinematically allowed. If, in contrast to the standard model, these spin-zero particles arise from dynamical symmetry breaking, then they are composite. While the concept of dynamical symmetry breaking is very attractive, specific additional assumptions are needed before concrete theoretical predictions can be obtained. At the present time, the most popular theory of this type is based on technicolor [2] and predicts the existence of spin-zero bosons of relatively low masses, called technipions. The mass of the charged technipions has been predicted to be in the range of 5 to 14 GeV [4]. The decays into the heaviest kinematically allowed quarks and leptons are favored. The ratio of the leptonic and hadronic decay rates can be substantial or very small depending on the specific assumptions used [5]. Our present experimental result, taken together with results from other experiments [6–9], shows that at the 95% confidence level there is no such spin-zero charged particle in the mass range of 5 to 13 GeV. We conclude that there are neither charged Higgs nor charged technipions in this mass range. This poses serious difficulties for standard technicolor schemes [4].

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The process under consideration is $e^+e^- \to H^+H^-$, where the symbol $H^\pm$ is used for both charged Higgs and technipions. For technipions, two solutions have been obtained for the relative abundance of decays into quarks and leptons [5]:

$$\frac{\Gamma(H^- \to \bar{c}s)}{\Gamma(H^- \to \tau^- \bar{\nu}_\tau)} = \frac{m_c^2}{m_\tau^2} \times \begin{cases} 1/3 & \text{solution I,} \\ 27 & \text{solution II.} \end{cases} \tag{1}$$

The first solution, where the leptonic decays dominate, was excluded by JADE [6] for the mass range $m_H = 4$–13 GeV by studying the decay modes:

$$e^+e^- \to H^+H^- \to (\tau\nu)\,(\text{hadrons}) \quad \text{and} \quad (\tau^-\bar{\nu})(\tau^+\nu). \tag{2}$$

Similar results were also obtained by CELLO [7], MARK J [8] and MARK II [9]. We show in this paper that solution II is excluded by our data on the process

$$e^+e^- \to H^+H^- \to \text{hadrons}. \tag{3}$$

The TASSO detector has been described elsewhere [10,11]. The event selection for one photon annihilation events of the type $e^+e^- \to$ hadrons follows exactly that described in ref. [12]. We required 5 or more charged particles with momentum component $P_{xy} > 0.1$ GeV/c transverse to the beam direction having polar angles θ satisfying $|\cos\theta| < 0.87$. Only charged particles were used and the sum of the charged particle momenta ΣP_i had to satisfy $\Sigma P_i > 0.265 W$ where W is the center-of-mass energy. The data used here correspond to a total integrated luminosity of 71.5 pb^{-1} at CM energies W between 33 GeV and 37 GeV (average $\overline{W} = 34.6$ GeV) yielding 20 046 hadronic events after the above event selection.

The search for reaction (3) is not entirely straightforward since it has a small production cross section [13],

$$d\sigma/d\Omega = (\alpha^2/8s)\beta^3 \sin^2\theta_H$$

and

$$R_{H^+H^-} = \sigma(e^+e^- \to H^+H^-)/\sigma(e^+e^- \to \mu^+\mu^-) = \tfrac{1}{4}\beta^3, \quad (4)$$

where $s = W^2$, β is the velocity of $H^\pm$ in the CM system and θ_H is the production angle with respect to the beam axis.

The accuracy reached in this experiment on a possible step in the total hadronic annihilation cross section is [12] $\Delta R < 0.50\,\beta^3$ at the 95% CL for $12.5 < m_H < 17$ GeV which does not permit us to rule out or prove the presence of reaction (3).

The $H^\pm$ decay into a quark and an antiquark (such as $c\bar{s}$ or $c\bar{b}$) will lead to two jets of hadrons; if both H^+ and H^- decay in this manner, the final state will consist of four jets. This event structure is different from that of the major background coming from $e^+e^- \to q\bar{q}$ and $e^+e^- \to q\bar{q}g$ (g = gluon) which leads to two and three jet events. We therefore searched for reaction (3) by looking for events with a four jet structure.

The topology of the four jet structure for events from reaction (3) depends strongly on the $H^\pm$ mass. At low $H^\pm$ masses the two jets from one of the $H^\pm$ mesons start to merge in the total CM system. For $H^\pm$ masses near the kinematical limit the four jets are well separated but the correct pairing is difficult to find. We therefore carried out the search for reaction (3) for m_H between 5 and 13 GeV in steps of 0.1 GeV. The four-jet analysis followed the procedure proposed in ref. [14] which basically performs first a three-jet analysis [15], removes the tracks of the slim jet, and performs again a three-jet analysis on the remaining tracks. The determination of the jet energies is modified from that of ref. [14] by introducing jet masses into the formalism instead of assuming massless jets. The observed velocity $\boldsymbol{\beta}_j^0$ of jet j is given by

$$\boldsymbol{\beta}_j^0 = \boldsymbol{p}_j^0/(\boldsymbol{p}_j^{02} + M_j^{02})^{1/2}, \quad (5)$$

where $\boldsymbol{p}_j^0$ is the vector sum of the momenta of the observed particles in jet j, and M_j^0 is the invariant mass of the observed particles (assumed to be pions) of jet j. The approximation is then made that the true velocity $\boldsymbol{\beta}_j$ of the jet is the same as the observed velocity $\boldsymbol{\beta}_j^0$. With this approximation the reconstructed energy of each jet is found from the energy–momentum conservation equation

$$\sum_{j=1}^{4} E_j\boldsymbol{\beta}_j = 0,$$

and

$$\sum_{j=1}^{4} E_j = 2E_{\text{beam}}, \quad (6)$$

where E_j is the reconstructed energy of jet j and E_{beam} is the energy of the e^+, e^- beam.

After the identification of the four jets, one has to decide which two jets should be grouped together to form a charged Higgs or technipion candidate of mass m_H. We make use of the fact that the energies of the two jets from $H^\pm$ decay have to add up to the beam energy and that both jet pairs have to have the same invariant mass. Defining m_{ij} as the invariant mass of jet i and jet j calculated from E_i, E_j, $\boldsymbol{\beta}_i$ and $\boldsymbol{\beta}_j$, we choose the pairings (i, j) and (k, l) out of the three possible ones by minimizing

$$(E_i + E_j - E_{\text{beam}})^2 + [\tfrac{1}{2}(m_{ij} + m_{kl}) - m_H]^2. \quad (7)$$

After the pairing is chosen, the jets are renumbered such that the jets 1 and 2 form one H while the jets 3 and 4 form the other H. The angle θ_H is then determined by the direction of the vector $E_1\boldsymbol{\beta}_1 + E_2\boldsymbol{\beta}_2$ (or $E_3\boldsymbol{\beta}_3 + E_4\boldsymbol{\beta}_4$).

We define θ_{ij} to be the opening angle between the jets i and j from $H^\pm$ decay, calculated from $\boldsymbol{\beta}_i$ and $\boldsymbol{\beta}_j$. The average opening angle and the difference between opening angles are then given by

$$\theta_{\text{av}} = \tfrac{1}{2}(\theta_{12} + \theta_{34}), \quad (8)$$

$$\Delta\theta = |\theta_{12} - \theta_{34}|. \quad (9)$$

Similarly the average mass is defined as

$$m_{\text{av}} = \tfrac{1}{2}(m_{12} + m_{34}). \quad (10)$$

Note that for each value of m_H, the expected event distribution is peaked at a particular value of θ_{av}.

The characteristics of $H^\pm$ production and decay were studied by means of a Monte Carlo event simulation. Two decay processes were studied:

Case (A) $e^+e^- \to H^+H^-$, $H^+ \to c\bar{s}$, $H^- \to \bar{c}s$

i.e. $H^\pm$ decay exclusively into $c\bar{s}$ quarks;

Case (B) $e^+e^- \to H^+H^-$, $H^+ \to c\bar{s}$ or $c\bar{b}$, $H^- \to \bar{c}s$ or $\bar{c}b$

with $H^\pm$ decaying equally into $c\bar{s}$ and $c\bar{b}$.

The choice of case (B) is motivated by the estimate [5,16]

$$\mathrm{Rate}\,(H^+ \to c\bar{b})/\mathrm{Rate}\,(H^+ \to c\bar{s}) \approx (m_b/m_c)^2 \sin^2\theta_3, \tag{11}$$

where θ_3 is a Kobayashi–Maskawa angle [17]. This ratio is less than 1 unless θ_3 is significantly larger than the Cabibbo angle [18].

In order to compare with the experimental data, it is necessary to choose a model for quark fragmentation into hadrons. We used the Field–Feynman procedure [19] with the same parameters as we determined and used previously [20]. In the notation of Field and Feynman, the values of the parameters are $a_F = 0.57$ for u, d, and s and $a_F = 0$ for c and b, $\sigma_q = 0.32$ GeV/c and $P/(P + V) = 0.56$.

The data were subjected to a number of cuts in order to maximize the signal of $e^+e^- \to H^+H^-$ over the background contribution from QCD processes. The QCD background was studied through a Monte Carlo program simulating the two-jet, three-jet and four-jet processes $e^+e^- \to \bar{q}q$, $q\bar{q}g$, $q\bar{q}gg$ and $q\bar{q}q\bar{q}$ [19–21] and in which second order corrections in α_s were fully implemented [22].

Cut (1). Since the production angular distribution for $e^+e^- \to H^+H^-$ is proportional to $\sin^2\theta$ while the dominant background process $e^+e^- \to q\bar{q}$ has a distribution proportional to $1 + \cos^2\theta$; we required $60° < \theta_H < 120°$.

Cut (2). The four-jet analysis [14] is most reliable when each jet has adequate energy. For this reason events were accepted if the observed jet energy E_j^0 satisfied

$$E_j^0 > 2.6 \text{ GeV} \tag{12}$$

and the reconstructed jet energy E_j satisfied

$$E_j > 3.6 \text{ GeV}. \tag{13}$$

Obviously this requirement removed also the events with negative reconstructed jet energy. In addition, for $5 \leqslant m_H \leqslant 7.5$ GeV we required

$$\sum_{j=1}^{4} E_j^0 > 0.58\cdot(2E_{\mathrm{beam}}). \tag{14}$$

Cut (3). Because the opening angles θ_{12} and θ_{34} are determined by the same m_H and the distributions of θ_{12} and θ_{34} are peaked at the same value which depends on m_H, the difference $\Delta\theta$ (in radians) between the opening angles was required to satisfy

$$\Delta\theta \begin{array}{ll} <0.15 & \text{for } m_H \leqslant 10\,\text{GeV}, \\ <0.01\, m_H + 0.05 \quad (m_H \text{ in GeV}) & \text{for } m_H \geqslant 10\,\text{GeV}. \end{array} \tag{15}$$

Figs. 1a, b and c show the Monte Carlo event distributions expected at $m_H = 10$ GeV for minimum E_j^0, minimum E_j and $\Delta\theta$, respectively, before the cuts (1) to (3) were applied. The positions of the cuts, as indicated on these figures, are not at the extreme ends of the distributions. As we discuss below, their calculated effect on any H^+H^- signal is altered only slightly by changes in assumptions on jet fragmentation.

We now describe the cuts made in the three variables $\Delta E = E_1 + E_2 - E_{\mathrm{beam}}$, m_{av} and θ_{av}. Note that the sign of ΔE changes if the jets 1 and 2 are interchanged with the jets 3 and 4. Figs. 1d, e and f show the two-dimensional plots in pairs of these three variables (for $m_H = 10$ GeV) after cuts (1) to (3) were made. For each event both ΔE and $-\Delta E$ were used and hence there are twice as many entries in figs. 1e, f as in fig. 1d. In each of the three figs. 1d, 1e and 1f, the events from $H^\pm$ decay populate approximately an ellipse. In the three-dimensional space of m_{av}, θ_{av} and ΔE, roughly speaking, the events fill an ellipsoid whose size and orientation depends on m_H.

By changing variables, the ellipsoid was transformed into a sphere described by a single parameter, its radius R. This allowed us to suppress background by a simple cut in R. We determined the parameters of the ellipsoid from $e^+e^- \to H^+H^-$ Monte Carlo events. We define [‡1]

‡For footnote see next page.

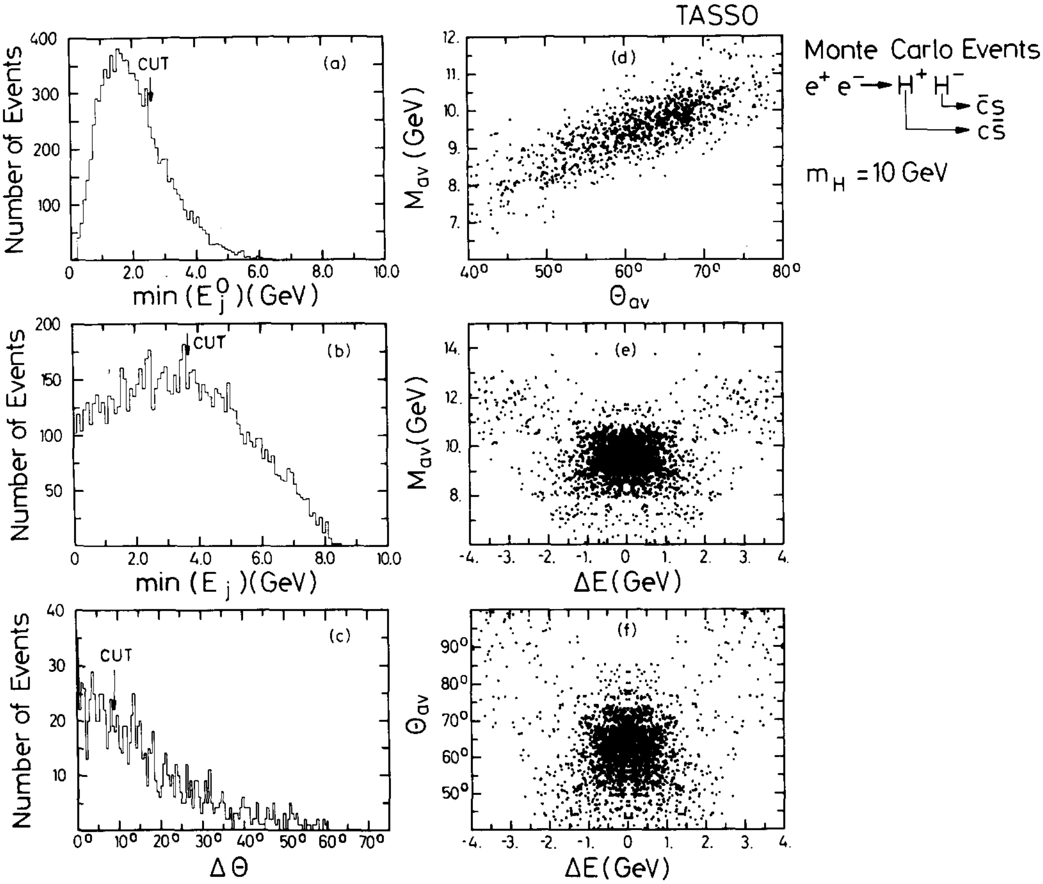

Fig. 1. (a) Monte Carlo event distribution of minimum visible jet energy, min (E_j^0), at m_H = 10 GeV. (b) Monte Carlo event distribution of minimum reconstructed jet energy, min (E_j), at m_H = 10 GeV. (c) Monte Carlo event distribution of the difference ($\Delta\theta$) between the two reconstructed opening angles of the two pairs of jets. Figs. 1 (a), (b) and (c) are distributions before the cuts (1) to (3) have been applied. Positions of cuts in min (E_j^0), min (E_j) and $\Delta\theta$ are indicated. (d) Two-dimensional Monte Carlo event distribution of the average reconstructed mass m_{av} versus the average reconstructed opening angle θ_{av} at m_H = 10 GeV. (e) Two-dimensional Monte Carlo event distribution of m_{av} versus ΔE (ΔE = difference between beam energy and the sum of the reconstructed energies of jet 1 and jet 2) at m_H = 10 GeV. (f) Two-dimensional Monte Carlo event distribution of θ_{av} versus ΔE. Figs. 1 (d), (e) and (f) are distributions after cuts (1) to (3) have been applied.

$$x_1 = \Delta E, \quad x_2 = m_{av} - \bar{m}_{av}, \quad x_3 = \theta_{av} - \bar{\theta}_{av}, \tag{16}$$

and for each given m_H form the tensor

$$T_{ij} = \sum_{\text{events}} x_i x_j, \tag{17}$$

summed over all Monte Carlo events from $H^\pm$ production, where $\bar{m}_{av}$ and $\bar{\theta}_{av}$ are the average values of m_{av} and θ_{av} for the Monte Carlo events. Note that $T_{12} = T_{13} = 0$, and that the ratio $T_{23}^2/(T_{22}T_{33})$ determines the tilt of the ellipsoid in the $m_{av} - \theta_{av}$ plane.

‡1 In order to define the parameters for the ellipsoid, we accepted Monte Carlo events after the cuts (1) to (3) with

$\Delta E < 0.01\, m_H^2$,

$4 + 0.94\,(m_H - 5) < m_{av} < 5.5 + 1.06\,(m_H - 5)$,

$(0.058\, m_H - 0.127) < \sin\frac{1}{2}\theta_{av} < (0.067\, m_H - 0.044)$,

with m_H and m_{av} in GeV. These cuts, introduced to remove the badly reconstructed four jet events, were applied only to the Monte Carlo events for defining R. They were not applied to the actual data.

T is a 3×3 symmetrical matrix. In terms of its inverse T^{-1}, the desired radial variable R for a given event is [‡2]

$$R = \Big(\sum_{ij} x_i T'_{ij} x_j \Big)^{1/2}, \tag{18}$$

where

$$T'_{ij} = T_{11} (T^{-1})_{ij}. \tag{19}$$

Note that x_i and hence R are defined for each event. For each m_H, the rms value of these R's is given by

$$R_{rms} = \Big(\sum_{\text{M.C. events}} R^2 / N_{\text{events}} \Big)^{1/2}, \tag{20}$$

where N_{events} is the number of Monte Carlo events generated at m_H.

Cut (4). For each given value of m_H, we require

$$R < R_{rms}. \tag{21}$$

The analysis was performed as follows. Monte Carlo events for $e^+e^- \to H^+H^-$ were generated in 1 GeV steps for m_H between 5 and 14 GeV. The relevant quantities for intermediate values of m_H were then obtained by interpolation. Fig. 2a shows, for $m_H = 10$ GeV, the event distribution in $(R/R_{rms})^3$ after cuts (1) to (3) both for the data and for the $H^\pm$ Monte Carlo events normalized to the total luminosity. Note that in fig. 2a, the observed events have $(R/R_{rms})^3 > 3$.

Fig. 2b shows the expected number of events for $e^+e^- \to H^+H^-$ on the basis of the Monte Carlo generation for case (A). The detection efficiency is found to be 0.8% for $m_H = 5$ GeV increasing to 1.5% for $m_H = 13$ GeV for case (A) and 0.6% for $m_H = 8$ GeV increasing to 1% for $m_H = 13$ GeV for case (B). The cuts (1) to (4) were applied to the experimental data increasing the value of m_H in steps of 0.1 GeV. The shaded area in fig. 2b shows the distribution of the data as a function of m_H. For a given mass m_H between 5 and 7.5 GeV, the number of surviving events was either 0 or 1; for m_H between 7.5 and 13 GeV no

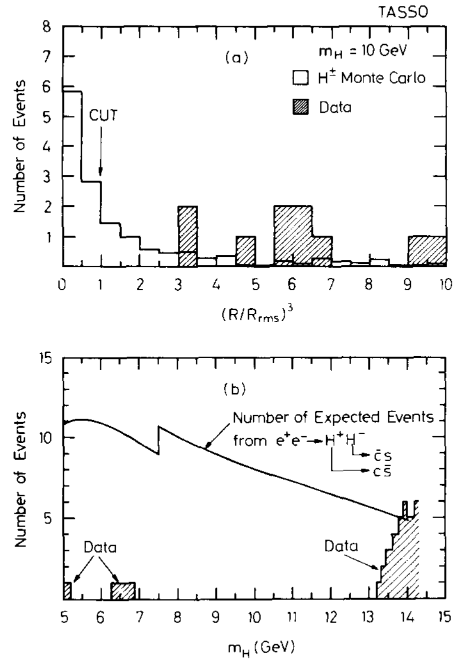

Fig. 2. (a) Monte Carlo and data (shaded) distributions of the one-dimensional variable $(R/R_{rms})^3$ (see text) analyzed at $m_H = 10$ GeV. The Monte Carlo distribution is normalized to the same total luminosity as the data. The position of cut (4) is indicated. (b) Number of events expected in this experiment after cuts (1) to (4) as a function of m_H for $e^+e^- \to H^+H^-$ with $H^+ \to c\bar{s}$, $H^- \to \bar{c}s$. Also shown is the number of events observed in our data as a function of m_H.

event was observed. The number of observed events is one order of magnitude less than the expected number shown in fig. 2b. The event distribution from the data as shown in fig. 2b, in particular the rapid rise of the observed number of events for m_H greater than 13 GeV, is reproduced by the QCD Monte Carlo program mentioned above, mainly through the process $e^+e^- \to q\bar{q}gg$.

We now discuss the systematic errors due to the uncertainty in the quark fragmentation parameters and to the choice of cuts. In the Monte Carlo simulation of the process $e^+e^- \to H^+H^-$, we studied the effects of: (i) changing σ_q from 0.32 GeV/c to 0.38 GeV/c which makes the four-jet structure of the events less distinct; (ii) using harder fragmentation functions for c and b as suggested by recent data [23]; (iii) reasonable variation in heavy meson decay branching ratios. In all cases, the detection efficiency

‡2 An equivalent definition for R is
$R = [(\boldsymbol{x}\cdot\hat{\boldsymbol{n}}_1)^2 + (\lambda_1/\lambda_2)(\boldsymbol{x}\cdot\hat{\boldsymbol{n}}_2)^2 + (\lambda_1/\lambda_3)(\boldsymbol{x}\cdot\hat{\boldsymbol{n}}_3)^2]^{1/2}$,
where $\boldsymbol{x}$ is the vector with the three components x_1, x_2 and x_3; $\hat{\boldsymbol{n}}_1, \hat{\boldsymbol{n}}_2$ and $\hat{\boldsymbol{n}}_3$ are the three unit eigenvectors of the tensor T_{ij}; and λ_1, λ_2, and λ_3 are the corresponding eigenvalues.

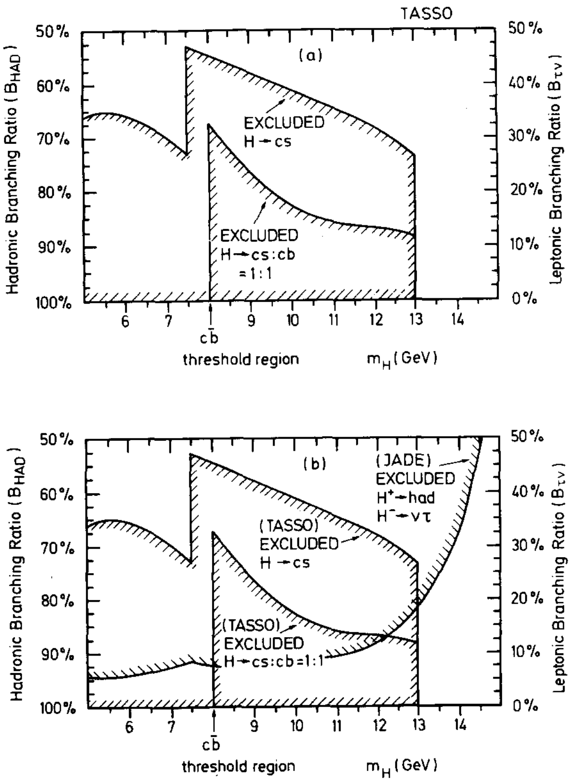

Fig. 3. (a) Limits on the hadronic branching ratio (B_{had}) as a function of $H^{\pm}$ mass from this experiment for case (A) $e^+e^- \to H^+H^-$ with $H^+ \to c\bar{s}$, $H^- \to \bar{c}s$ and for case (B) $e^+e^- \to H^+H^-$ with $(H \to cs) : (H \to cb) = 1 : 1$. The shaded area is excluded at the 95% confidence level. The vertical scale on the right hand side of the figure indicates the corresponding leptonic branching ratio ($B_{\tau\nu}$) if the sum of $B_{\mathrm{had}} + B_{\tau\nu} = 1$. (b) Limits on the leptonic branching ratio from JADE for $H^+ \to \tau^+\nu$, $H^- \to \tau^-\bar{\nu}$ or $H^+ \to \tau^+\nu$, $H^- \to$ hadrons superimposed on fig. 3(a).

for $e^+e^- \to H^+H^-$ changed by less than 15%. The results shown in figs. 2 and 3 correspond to the least favorable case obtained from these variations. We also repeated the entire analysis relaxing the limits of the cuts (2) and (3) by 10% and at the same time tightening cut (4) such that the expected number of $e^+e^- \to H^+H^-$ events was unchanged from that shown in fig. 2b. The number of events found in the data remained 0 or 1 using these changed cuts.

Taking the number of events observed after cuts (1) to (4) to be one for m_H between 5 and 7.5 GeV, and zero between 7.5 and 13 GeV, fig. 3a shows as a function of m_H the upper limits (95% confidence level) for the hadronic branching ratio $H \to c\bar{s}$ (case A) and $H \to c\bar{s}, c\bar{b}$ (1 : 1) (case B). One would expect that a true situation lies somewhere between these two cases [see eq. (11) above]. In addition, the result in case A also applies to the case of $H \to u\bar{d}$. The jump in the upper limit for case A at $m_H = 7.5$ GeV as shown in fig. 3a reflects the discontinuity in the number of experimentally observed events just mentioned and the change of cut [see eq. (14)]. As shown in fig. 3a, the upper limit on the hadronic branching ratio is everywhere less than 90% and hence excludes solution II of eq. (1).

In fig. 3b our result is shown together with the JADE result [6]. Taken together, the two experiments exclude the existence of a pointlike charged scalar particle with decay modes as discussed above in the mass range between 5 and 13 GeV.

In conclusion, we have searched for pair production of charged pointlike scalars decaying predominantly into hadrons by using a four-jet analysis. Setting aside the possibility of severe mixing of generations in the Kobayashi–Maskawa scheme, we exclude the existence of such scalars with masses between 5 and 13 GeV decaying into hadrons. Using in addition results of searches [6–9] for pair production of scalars with at least one decaying leptonically, we exclude the existence of pointlike charged scalar particles with masses between 5 and 13 GeV.

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