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Production of heavy charged Higgs particles at very high energies

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The production of heavy charged Higgs bosons at very high energies (LEP) is investigated. It turns out that, in favorable circumstances, charged scalars of mass 50-100 GeV could be detected and be even more copiously produced than the standard neutral Weinberg-Salam-type Higgs particle of the same mass.

There are a number of reasons that induce us to contemplate the existence of charged Higgs particles. Among them, we may list a few. (i) The existence, for no known reason, of at least three fermion families makes the existence of more than one Higgs family plausible. (ii) Left-right-symmetric models require two doublets.[1] (iii) The mass hierarchies of the fundamental particles may suggest various Higgs scalars as their possible origin.[2] (iv) Cabibbo mixings may be implemented with the help of different Higgs multiplets.[3] But, above all, the fact that the symmetry-breaking mechanism is a key ingredient of present unified field theories of electroweak interactions, leads us to explore in detail any model possibly realized in nature. Many production mechanisms and detection aspects of both neutral and charged Higgs bosons have been discussed in the literature.[4] In particular, Jones and Petcov have investigated the production of very massive standard Weinberg-Salam (WS) Higgs scalars in e^+e^- collisions in the LEP energy range.[5] Here, we shall be concerned with an extension of their work, namely the production of heavy charged Higgs scalars in e^+e^- annihilation at LEP (up to ~ 200 GeV). We shall see that under favorable circumstances it may be easier to detect a charged Higgs boson than its neutral counterpart.

Almost any SU(2)×U(1) model but the simplest one, i.e., the WS model, is endowed with physical charged Higgs particles. The processes which we shall study, and which involve these particles, are

$$e^+e^- \to H^\pm X^\mp \ , \tag{1}$$

where $X^\mp$ stands for either $(X^-,X^+)\equiv(l^-,\ \bar\nu_l;\ l^+\nu_l)$ or $X^\mp\equiv$ hadrons. The diagrams involved in our calculation are shown in Fig. 1.[6] There, $(q,\ q')$ stand for (u,d), (c,s), or (t,b) and where for the sake of simplicity in notation we neglect all Cabibbo-type mixings.

Our working definition of a heavy Higgs boson will be

$$\sqrt{s}-M_W-30\ \text{GeV} \lesssim m_H \lesssim \sqrt{s}-M_W$$

with $\sqrt{s}\sim 140$ to 200 GeV. For lower mass values, other processes than those in Eq. (1) render better rates.

The total cross section $\sigma(ee\to HX)$ is given essentially by the sum of the squares of each amplitude in Fig. 1, since the interference of both is practically negligible. This is because diagram (a) in Fig. 1 strongly resonates at an invariant mass M_W of the lepton pair and is therefore $\pi/2$ out of phase with respect to diagram (b) of Fig. 1.

For the s-channel contribution one easily obtains

$$\sigma^{(a)} \simeq \frac{4G^3K^2M_W^{\,6}}{3\pi^3\sqrt{2}}\ \frac{\rho(\lambda_V^{\,2}+\lambda_A^{\,2})}{(s-M_Z^{\,2})^2/M_Z^{\,2}+\Gamma_Z^{\,2}}\ \frac{f(u_0)}{2\beta} \times\left[\tan^{-1}\left(\frac{\alpha-2A}{\beta}\right)-\tan^{-1}\left(\frac{\alpha-2B}{\beta}\right)\right] , \tag{2}$$

where

$$\lambda_V=-(\tfrac{1}{4}-\sin^2\theta_W)\ \text{and}\ \lambda_A=-\tfrac{1}{4}\ ,$$

the function $f(u)$ is defined as

$$f(u)=(u^2-m_H^{\,2}/s)^{1/2}(1-2u+\tfrac{1}{3}u^2+\tfrac{2}{3}m_H^{\,2}/s)$$

and u_0 in $f(u_0)$ stands for

$$u_0=\tfrac{1}{2}(1+m_H^{\,2}/s)-M_W^{\,2}/2s\ .$$

α and A are given by

$$\alpha=1+(m_H^{\,2}-M_W^{\,2})/s,\quad A=m_H^{\,2}/\sqrt{s}$$

and β and B by

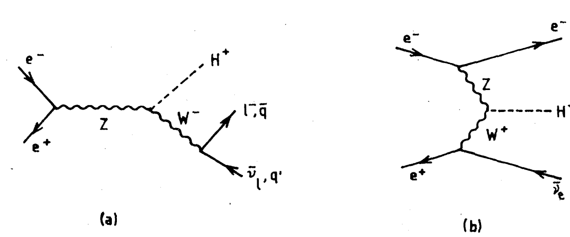

FIG. 1. Diagrams for heavy-charged-Higgs-boson production.

$\beta = M_W \Gamma_W / s$ and $B = \frac{1}{2}(1 + m_H{}^2/s)$.

K is the coupling strength associated to the WZH vertex and which is given by

$$gKW^\mu Z_\mu H \; .$$

In formula (2) above, ρ stands for $\rho \equiv M_W{}^2 / M_Z{}^2 \cos^2\theta_W$. In our actual numerical analysis we shall narrow down the class of possible models by taking $\rho \simeq 1$. This choice is dictated by the present phenomenological evidence which supports $\rho = 1$ within a few percent error.[7]

Equation (2) is only approximate. However, it is an excellent approximation since it differs from the exact formula only in a few percent (below 5%) in the whole range of masses and c.m. energies considered here.

The calculation of the t-channel diagram is somewhat more cumbersome and the final result involves a triple integration which must be performed numerically. It reads

$$\sigma^{(b)} = \frac{G^3 K^2 M_W{}^6 \rho}{\pi^3 \sqrt{2}} \int_0^{1/2(1-m_H{}^2/s)} dx \int_{-1}^{1} dy \int_{-1}^{1} dz \, \frac{x}{[sx(1-z)/M_Z + M_Z]^2} \, R(x,y,z) \; , \tag{3}$$

where

$$R(x,y,z) = [2(\lambda_V - \lambda_A)^2 + (\lambda_V + \lambda_A)^2 x(1-y)(1+z)] g(x,y,z) - 2(\lambda_V - \lambda_A)^2 h(x,y,z) \; .$$

Here,

$$g(x,y,z) = \frac{1}{(1+y)^2} \left[\frac{1}{(a^2 - b^2)^{1/2}} - \frac{2c^2 - ac - b^2}{(c^2 - b^2)^{3/2}} \right]$$

and

$$h(x,y,z) = \left(\frac{s - m_H{}^2 - 2sx}{2M_W{}^2} \right)^2 \frac{c}{(c^2 - b^2)^{3/2}}$$

with a, b, c given by

$$a = 1 - x + xyz \; ,$$

$$b = x(1-y^2)^{1/2}(1-z^2)^{1/2} \; ,$$

$$c = a + \frac{s - m_H{}^2 - 2sx}{2M_W{}^2}(1+y) \; .$$

Equation (3) also contains the constant K. This constant depends on the particular model chosen and is optimistically assumed to be of $O(1)$ in the literature.[4,8] We shall do so also, without discussing any specific model at all.[9]

Taking for the Weinberg angle the value $\sin^2\theta_W = 0.23$, which implies $M_W \simeq 80$ GeV and $M_Z \approx 90$ GeV, we obtain for the total $e^+e^- \to H^\pm X^\mp$ cross section the curves plotted in Figs. 2–4. They show $\sigma(ee \to HX)$ for various c.m. energies and for a range of Higgs-boson masses. These curves are

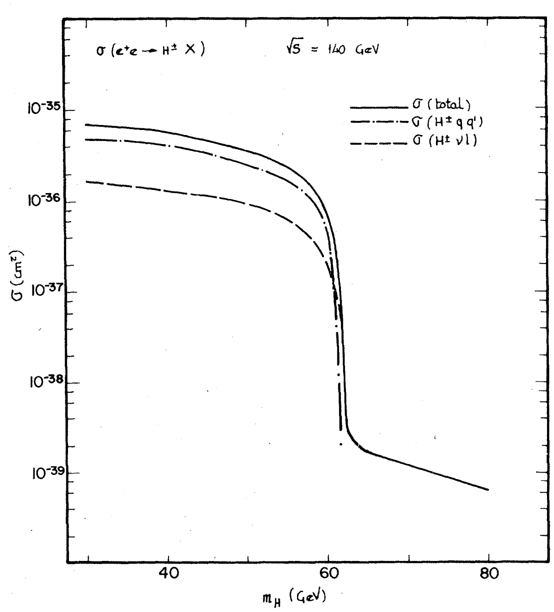

FIG. 2. Total cross sections for heavy-charged-Higgs-boson production as a function of mass for $\sqrt{s} = 140$ GeV.

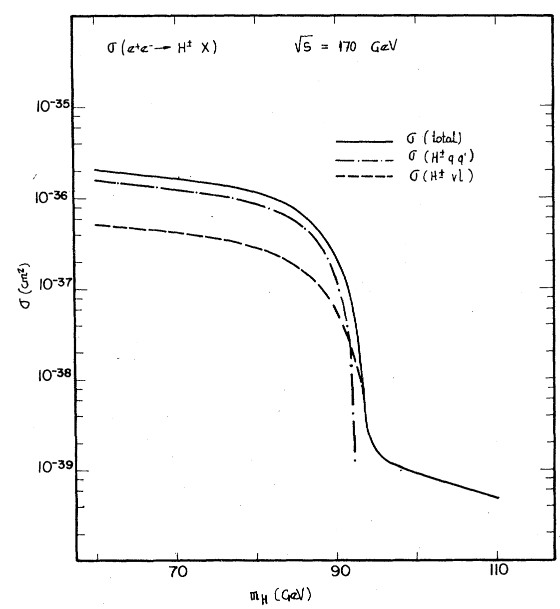

FIG. 3. As in Fig. 2 for $\sqrt{s} = 170$ GeV.

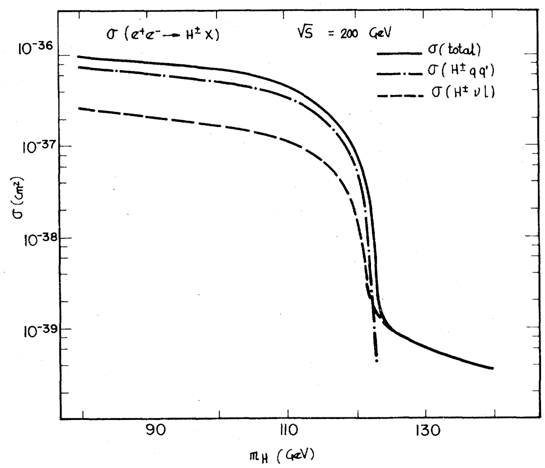

FIG. 4. As in Fig. 2 for $\sqrt{s}=200$ GeV.

to be interpreted as follows. We give separately in each figure the sum over leptonic modes ($l=e$, μ, τ) and the sum over hadronic modes, respectively, the latter being just the sum over color and flavor of the quark cross sections ($X \equiv \bar{q}q'$). Although no experimental evidence for the t quark has been found yet, we have included it in our calculations, in the assumption that its mass can be excited well above threshold at LEP energies. A note of caution, however, is in order. Our formulas have been derived in the assumption that the fermion masses are small compared to the intermediate-vector-boson masses. This could be evidently false for the t quark. Nevertheless, for our purposes, and since we cannot do better (m_t is not known) we have ignored effects on the cross section due to a possibly very large t-quark mass. We observe that the hadronic cross section falls off abruptly at a Higgs-boson mass m_H given by the relation $\sqrt{s} \simeq m_H + M_W$, as it should, since to the $ee \to H+$hadrons cross section only the annihilation channel contributes and its contribution is mainly concentrated around an invariant mass of the two-quark system equal to the W-boson mass. Consequently, phase space is exhausted for Higgs-particle masses larger than the mass m_H given by the above relation. The third curve given on each figure corresponds to the total cross section, i.e., the sum of the leptonic and hadronic cross sections. With the planned LEP luminosity of 10^{32} cm^{-2} s^{-1}, our calculated cross sections lead us to expect production rates of one event/week to a few dozen events/day, depending on the c.m. energy and mass of the produced scalar bosons. We notice that these rates are always larger than the corresponding rates for neutral boson production and may even be as much as a factor of 10 larger (see Ref. 5).

Experimental detection of Higgs particles will be an obviously difficult task. Nevertheless, they possess a unique signature, namely, they tend to decay preferentially into particles of high mass. We therefore expect in most of the events either (a) four-quark jets or (b) two-quark jets plus a lepton pair. $H^{\pm}$ decaying into leptons is strongly disfavored and consequently four leptons in the final state should be rarely seen. In both cases, (a) and (b), two jets (the ones coming from the decaying scalar boson) carry most probably heavy flavors, e.g., one jet carries top flavor and the other jet carries beauty. For case (a), the other pair of jets may contain the flavors u and d, c and s, or t and b, respectively, with equal probability. Finally, in case (b), missing energy and a charged lepton with unbalanced momentum would be observed in addition to the flavored heavy-quark jets.

As far as background is concerned, estimates give cross sections typically on the order of 10^{-39} cm^2 or less. In fact, a main source of background in the kinematical domain considered should be the production of the intermediate vector boson $W^{\pm}$, either real or virtual, along with a fermion pair (e.g., $e^+e^- \to W^+ e\bar{\nu}$), and its subsequent decay to heavy flavors. Obviously, an event like this could be mistaken for an event in which a produced Higgs boson decays into heavy quarks. However, even in the case of real $W^{\pm}$ production[10] (i.e., for an invariant mass of the heavy-flavored $\bar{q}q'$ system equal to M_W), the ratio signal to noise is very high. Indeed, at a c.m. energy of 170 GeV, one may expect 100 to 200 events originating from Higgs-scalar decay for every event of the alternative type. In any other situation, in which the heavy Higgs meson has a chance to be detected, the ratio of signal to noise is even better.

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