Ref.TH.2661-CERN

HEAVY HIGGS BOSONS AT LEP

D. R. T. Jones

CERN - Geneva

and

S.T. Petcov

CERN - Geneva

and

Institute of Nuclear Research and Nuclear Energy
Bulgarian Academy of Sciences - Sofia

A B S T R A C T

Production of a heavy Weinberg-Salam type neutral Higgs boson at LEP energies is considered. We conclude that the Higgs is unlikely to be detected at LEP if its mass is greater than 150 GeV.

Ref.TH.2661-CERN
24 April 1979

The possible construction in Europe of a large e^+e^- colliding beam machine (LEP) capable of centre-of-mass energies up to ~ 200 GeV (i.e., far beyond those accessible at PETRA and PEP) is currently subject to intensive study ¹⁾. In this note we consider the production in e^+e^- collisions at LEP energies of a heavy neutral Higgs boson.

Physical Higgs particles are predicted by all spontaneously broken gauge theories of weak and electromagnetic interactions, but their number and properties (charges, masses and couplings) depend on the theory. We limit our discussion to the standard Weinberg-Salam model with one physical Higgs particle (H), six leptons (ν_l, l^- ; $l = e, \mu, \tau$) and six tricoloured quark flavours (u, d, s, c, b, t). Then, for a given value of the initial c.m. energy $\sqrt{s}$, we mean by a heavy Higgs boson one of mass $m_H \gtrsim M_Z$ and $m_H \gtrsim \sqrt{s} - M_Z$ where M_Z is the mass of the neutral vector boson (Z^0).

The production of lighter Higgses at LEP energies has been extensively discussed ²⁾. For $\sqrt{s} - M_Z < m_H < M_Z$ and $\sqrt{s} > M_Z$ the following processes have been suggested as suitable ^{3), 4)}:

$$e^+e^- \longrightarrow Z^0, \quad Z^0 \longrightarrow H + l^+ + l^- \quad (1)$$

and

$$e^+e^- \longrightarrow Z^0, \quad Z^0 \longrightarrow H + \gamma \quad (2)$$

Both give cross-sections $\sim 10^{-37} \text{ cm}^2$ for m_H as high as 60 GeV. Estimates of background effects, however, show ²⁾ that detection of reaction (1) may be difficult (but probably possible), while the identification of reaction (2) may turn out to be practically impossible.

For $m_H < \sqrt{s} - M_Z$ the process

$$e^+e^- \longrightarrow Z^0 + H \quad (3)$$

is probably the best source of Higgses ⁵⁾. Cross-sections $\sim 10^{-37} \text{ cm}^2$ are available not far from threshold (in particular, for $m_H \lesssim 100$ GeV if $\sqrt{s} = 200$ GeV and $M_Z = 94$ GeV) and in this case no severe background problems are anticipated ²⁾.

As is well known, theoretical constraints on the Higgs mass are not stringent, and permit any value in the range 10 GeV to ~ 1 TeV ⁶⁾. Therefore it is worth while considering the possibility that the Higgs is heavy. The

significance of our definition of a heavy Higgs is now easily seen : its mass is such that it cannot be produced in the reactions (1)-(3) with a feasible cross-section. At present it is difficult to foresee what the feasibility limit cross-section for Higgs production at LEP will be; for comparison purposes we shall use (probably optimistically) the value $2 \cdot 10^{-38} \text{ cm}^2$. With the projected LEP luminosity this corresponds to a production rate of 1 event/week.

The heavy Higgs would be produced in high energy e^+e^- collisions mainly in association with a fermion-antifermion pair :

$$e^+e^- \longrightarrow H + f + \bar{f} \quad (4)$$

where $f = \nu_e, \dots, e, \dots, u, \dots, t$. One contribution to the cross-section for this process arises from the graph (A)

which corresponds to process (1) or (3), respectively, when the first or the second of the Z^0 propagators is on mass shell. However, there are additional contributions from diagrams (B)-(D) :

Diagram (D) gives a negligible contribution as long as there are no leptons or quarks with masses of $O(M_W)$ or greater ⁷⁾ (which we assume throughout).

We have calculated the total cross-sections for heavy Higgs production in association with an e^+e^- pair, $\sigma(H e^+e^-)$, a $\mu^+\mu^-$ ($\tau^+\tau^-$) pair, $\sigma(H \mu^+\mu^-)$ ($\sigma(H \tau^+\tau^-) = \sigma(H \mu^+\mu^-)$) with a pair of any neutrinos, $\sigma(H \nu \bar{\nu})$, of any quarks, $\sigma(H q \bar{q})$ and finally with any fermion-antifermion pair $\sigma(H f \bar{f})$. All these cross-sections receive contributions from diagram (A), which for a given f have the form

$$\sigma_{f\bar{f}}^{(A)} = \frac{G_F^3 M_Z^4}{12\pi^3 \sqrt{2}} \left(\frac{M_Z^2}{s} \right)^2 (v_e^2 + a_e^2)(v_f^2 + a_f^2) \times$$

$$\frac{\int_0^{\sqrt{u^2 - \frac{m_H^2}{s}}} \left(1 + \frac{2}{3} \frac{m_H^2}{s} - 2u + \frac{1}{3} u^2 \right) du}{\left(1 - \frac{M_Z^2}{s} \right)^2 \left[\left(1 + \frac{m_H^2 - M_Z^2}{s} - 2u \right)^2 + \frac{M_Z^2 \Gamma_Z^2}{s^2} \right]} \quad (5)$$

Here $u\sqrt{s}$ is the Higgs energy :

$$\frac{m_H}{\sqrt{s}} \leq u \leq \frac{1}{2} \left(1 + \frac{m_H^2}{s} \right)$$

Γ_Z is the total Z^0 width and v_f and a_f are the appropriate neutral current couplings of fermion f in the Weinberg-Salam model. (For example, $v_e = -\frac{1}{2} + 2\sin^2\theta_W$, $a_e = -\frac{1}{2}$, $v_{\nu_e} = a_{\nu_e} = \frac{1}{2}$, etc.). The integration over the momenta of the final state fermions f was performed neglecting their masses. For the values of m_H and in the kinematical regions considered, this approximation is justified.

The t channel diagrams (B) and (C) and the interference terms between diagrams (B) and (A) (when $f = \nu_e$) and (C) and (A) (when $f = e^-$) give contributions to $\sigma(H\nu\bar{\nu})$ and $\sigma(He^+e^-)$, respectively. At the high energies under consideration here, the momentum transferred in the $W^\pm$ and Z^0 propagators in diagrams (B) and (C) can be of the order of M_W or M_Z and therefore cannot be safely neglected^{*}). Both t channel and interference terms were reduced to the form of three-dimensional integrals, which were then evaluated numerically. For example, the following expression was obtained for the contribution of diagram (B) to $\sigma(H\nu\bar{\nu})$:

$$\sigma^{(B)}(H\nu\bar{\nu}) = \frac{G_F^3 M_W^4}{4\pi^4} \int_0^{\frac{1}{2}(1 - \frac{m_H^2}{s})} dx \int_{-1}^1 dy \int_{-1}^1 dz x^2 (1+y)(1-z) \times$$

(6)

^{*}) In an earlier version of this work [Ref. 8)] the momentum transfer was neglected. This resulted in an over-estimation (by a factor of about 4) of the contributions of diagrams (B) and (C), and consequently somewhat more optimistic conclusions than we reach here.

$$\times \frac{P^2(1+z)^2}{\left[1 + \frac{s}{M_W^2} x(1-y)\right]^{\frac{1}{2}}} \frac{1}{P} \left\{ \frac{2}{P} \left[\frac{1}{\sqrt{Q^+ Q^-}} \operatorname{arctg} \left(\sqrt{\frac{Q^+}{Q^-}} \operatorname{tg} \frac{\pi}{\sqrt{2}} \right) - \frac{1}{\sqrt{P^+ P^-}} \operatorname{arctg} \left(\sqrt{\frac{P^+}{P^-}} \operatorname{tg} \frac{\pi}{\sqrt{2}} \right) \right] \right. \\ \left. + \frac{1}{P^+ P^-} \left[\frac{(Q^- - Q^+) \sin \sqrt{2} \pi}{\bar{P} + P^+ + (Q^- - Q^+) \cos \sqrt{2} \pi} - \frac{(\bar{P} + P^+)}{\sqrt{P^+ P^-}} \operatorname{arctg} \left(\sqrt{\frac{P^+}{P^-}} \operatorname{tg} \frac{\pi}{\sqrt{2}} \right) \right] \right\} \quad (6) \\ \text{Ctd.}$$

Here $\sqrt{s}$ is the energy of ν_e , y and z are the cosines of the angles between the electron momentum and the momenta of ν_e and $\bar{\nu}_e$ respectively, and

$$P = \frac{s - m_H^2 - 2sx}{2M_W^2} (1+z) \\ Q^\pm = 1 - x (1 - yz \pm \sqrt{1-y^2} \sqrt{1-z^2}) \\ P^\pm = Q^\pm + P$$

The results of our calculations are presented graphically in Figs. 1-4, where the dependence of the various cross-sections on m_H for $\sqrt{s} = 140, 170, 200$ and 240 GeV are shown. The figures were obtained using $M_Z = 94$ GeV and $M_W = 84$ GeV (i.e., for $\sin^2 \theta_W = 0.20$).

The heavy Higgs would be produced chiefly with a pair of quarks or neutrinos, the cross-section $\sigma(H\nu\bar{\nu})$ being 2-3 times smaller than $\sigma(H\nu\bar{\nu})$ and approximately 10 times smaller than $\sigma(Hq\bar{q})$ for almost all values of m_H considered. Due to the contribution of the t channel diagrams, $\sigma(H\nu\bar{\nu})$ and $\sigma(H\nu^+e^-)$ do not decrease so rapidly as $\sigma(Hq\bar{q})$ and $\sigma(H\nu_\mu^+\mu^-)$ as m_H is increased. This effect, however, is considerable only for values of m_H where the cross-sections are $\sim 10^{-39}$ cm² or smaller.

The Weinberg-Salam type Higgs is expected to decay mostly into a pair of the heaviest fermions available, since its couplings to leptons and quarks are proportional to their masses. In the standard model with six leptons and six quark flavours this would be a pair of t quarks if $2m_t < m_H$ or b quarks if $2m_t \gtrsim m_H$. Then the associated production of a heavy Higgs with a pair of quarks would lead to the observation of four quark jets, while in the case of production with a pair of neutrinos only two quark jets moving

in roughly the same direction with an uncompensated momentum and a large amount of missing energy would be observed. Preliminary estimates of the background process cross-sections show that in the kinematical region considered they are $\sim 10^{-39} \text{ cm}^2$ or smaller.

Our general conclusion is that the considered mechanism for Higgs boson production may be important for

$$\sqrt{s} - M_Z - 5 \text{ GeV} \lesssim m_H \lesssim \begin{cases} \sqrt{s} - M_Z + 25 \text{ GeV} & \sqrt{s} \sim 140 \text{ GeV} \\ \sqrt{s} - M_Z + 10 \text{ GeV} & \sqrt{s} \sim 170 \text{ GeV} \\ \sqrt{s} - M_Z + 5 \text{ GeV} & \sqrt{s} \sim 200 \text{ or } 240 \text{ GeV} \end{cases}$$

The upper bounds of the regions correspond to $(\sigma(Hq\bar{q}) + \sigma(H\nu\bar{\nu})) \simeq 2 \cdot 10^{-38} \text{ cm}^2$. In the case $\sqrt{s} \sim 140 \text{ GeV}$ our conclusion reflects the possibility that Higgs production via Z^0 decays may be impossible to separate from background.

The results remain practically unaltered for $0.2 \lesssim \sin^2 \theta_W \lesssim 0.3$. Obviously the cross-sections $\sigma(Hq\bar{q})$ and $\sigma(H\nu\bar{\nu})$ would be larger if the number of "light" quark flavours and neutrinos were greater than six and three, respectively.

We thank John Ellis for discussions and encouragement, and Jan Finjord for showing us his results prior to publication.

R E F E R E N C E S

- 1) Proceedings of the LEP Summer Study, CERN Yellow Report 79-01 (1979).
- 2) G. Barbiellini et al., The production and detection of Higgs particles at LEP, ECFA/LEP Working Group, SSG/9/5 (1979).
- 3) J.D. Bjorken, Proceedings of the 1976 SLAC Summer Institute, SLAC-198 (1976);
J. Finjord, ECFA/LEP Working Group, SSG/9/4 (1979) and CERN preprint TH.2663 (1979).
- 4) R.N. Cahn, M.S. Chanowitz and N. Fleishon, UC preprint LBL-8495 (1978).
- 5) J. Ellis, M.K. Gaillard and D.V. Nanopoulos, Nuclear Phys. B106, 292 (1976);
B.L. Ioffe and V.A. Khoze, Leningrad preprint LINP-274 (1976);
S.L. Glashow, D.V. Nanopoulos and A. Yildiz, Harvard preprint HUTP-78/A012 (1978).
- 6) For discussions and references, see, e.g. :
J. Ellis, Proceedings of the 1978 SLAC Summer Institute SLAC-215 (1978);
also available as SLAC-PUB-2177 (1978).
- 7) K.J.F. Gaemers and G.J. Gounaris, Phys.Letters 77B, 379 (1978).
- 8) D.R.T. Jones and S.T. Petcov, ECFA/LEP Working Group SSG/9/3 (1979).

FIGURE CAPTIONS

- Figures (A)-(D) : Diagrams for heavy Higgs boson production in association with a pair of leptons or quarks.
- Figures 1 - 4 : Total cross-sections for heavy Higgs boson production as functions of m_H for $\sqrt{s} = 140, 170, 200$ and 240 GeV, respectively ($\sin^2 \theta_W = 0.20$).

FIG. 1

FIG.2

FIG. 3

FIG. 4