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Searching for Light Higgs Scalar Bosons in the Next Generation of Electron–Positron Collider at LEP

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The e^+e^--collider facilities at LEP II, with the CM energy $\sqrt{S}$ in the range 100–170 GeV, may be able to detect "light" Higgs bosons, assuming a high luminosity. The production cross sections of a light Higgs boson H^0 in association with the neutral gauge boson Z^0 are calculated for varying ranges of the CM energy expected to be available to LEP II and VLEEP (Novosibirsk) and for various values of the light Higgs mass. It is found that production cross sections are sizable in comparison with those for the very massive Higgs bosons in proton-anti(proton) supercolliders, Tevatron, $Sp\bar{p}S$, and SSC, respectively. The implication of this feature is pointed out. Further, prospects for light Higgs production in association with the charged gauge boson W^- in ultraenergetic neutrino beams are examined.

1. INTRODUCTION

The standard model of electroweak interactions of Glashow, Weinberg, and Salam (Glashow, 1961; Weinberg, 1967; Salam, 1968; Salam and Ward, 1964) has been successful in describing weak and electromagnetic phenomena and quantum chromodynamics (Politzer, 1974; Marciano and Pagels, 1978), which is now virtually accepted as the theory of the strong interaction. Thus, all of particle physics phenomena, including the recent discovery of the $W^\pm$ and Z^0 bosons (Arnison et al., 1983a-c; Banner et al. 1983; Bagnaia et al., 1983) fit well with what has come to be called the standard model, a gauge theory based on $SU(3)\times SU(2)\times U(1)$. Only one piece in the puzzle is missing—the spin-zero elementary Higgs boson, which is needed by the standard model for spontaneous symmetry breaking, responsible for the masses for the $W^\pm$, Z, and fermions. Although the couplings of the Higgs boson to quarks, leptons, and the intermediate

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charged and neutral gauge bosons are provided by the standard electroweak theory, the Higgs boson mass is not. It is simply a parameter in the standard model that is entirely unconstrained by present experimental evidence. Theoretical considerations (Linde, 1976), however suggest that the Higgs boson mass must exceed 4 GeV/c^2 and a conditional upper bound on the mass had been derived (Lee et al., 1977; Ellis, 1978; Ali, 1981; Weinberg, 1976; Veltman, 1977):

$$7\ \mathrm{GeV}/c^2 \lesssim m_{H^0} \lesssim \mathrm{TeV}/c^2 \tag{1}$$

Various problems appear to have been responsible for the delay in the detection of the Higgs boson in experiments. One is its mass, which is presumed to be very heavy, in the range $m_{H^0} \lesssim 1$ TeV/c^2, with the implication that detection of the boson could only occur in selected experiments, particularly those to be conducted at multi-TeV $\bar{p}p$ and pp colliders (Tevatron and SSC, respectively). The two accelerators, expected to be turned on in a couple of years (Haber and Kane, 1985), may have a maximum CM energy in the ranges 2 and 40 TeV, respectively, with luminosities of 10^{34}-10^{31} and 10^{33} cm^{-2} sec^{-1}, respectively. However, in experimental searches for the Higgs boson, it appears that two categories of the boson are being aimed at, depending on which appears. One category is a Higgs boson with mass less than that of the intermediate gauge boson W. Such a Higgs boson is said to be light. The other category of the boson is presumed to have a mass greater than twice that of the W boson. Such a Higgs boson is said to be massive. The conditional upper bound of $m_{H^0} \leq$ TeV/c^2 on the Higgs boson mass leads naturally to the contemplation of this heavy Higgs boson alternative, with $m_{H^0} \geq 2M_w$. It is thought that the $\bar{p}p$ and pp supercolliders will be ideal for the exploration of these massive Higgs boson, while light Higgs bosons can be searched for in the next generation of e^+e^- colliders, namely SLAC at Stanford, with CM energy $\sqrt{S} \approx 0.1$ TeV (Richter, 1982), and LEP II at CERN, with $\sqrt{S} \approx 0.1$-0.2 TeV (Schopper, 1983). It has been suggested that it may be possible to search for Higgs bosons with masses as large as 100 GeV/c^2 at LEP II (Marciano, 1985) via $e^+e^- \to Z^0H^0$ if high luminosity is achieved. Higher energy e^+e^- colliders with the CM energy of the order of 2 TeV (SLEEK) are also being contemplated (Cashmore, 1985). The expectation, therefore, is that should Higgs particles exist with mass m_{H^0} (or even $m_{H^\pm}$) < 100 GeV/c^2, which correspond to neutral (charged) Higgs, they will be observed at LEP II (at SLAC, if the masses are lower). Since the backgrounds are fierce at the hadron colliders and rates too low in ep colliders, LEP II is being considered as the best Higgs machine.

With the high prospects for the e^+e^--collider facilities at LEP II and SLAC in view, I have calculated light neutral Higgs boson production cross sections via the interaction

$$e^+e^- \to Z^0H^0 \tag{2}$$

for varying ranges of the CM energy $\sqrt{s}$ expected to be available to the e^+e^- machines in the near future, namely LEP, SLAC and VLEEP (Balakin and Skrinsky, 1981), and for various values of light Higgs mass, in readiness for confrontation with experiment as soon as beam facilities become available. The calculated cross sections are compared with those for the production of massive Higgs bosons in the next generation of proton–anti(proton) colliders. I have also gone further to look at the prospects for light Higgs boson associated production in ultrahigh-energy neutrino beams via the process

$$\bar{\nu}_e e^- \to W^-H^0 \tag{3}$$

This process is in a way parallel to (2) and may be relevant to the DUMAND (deep underwater and muon neutrino detector) project, whose purpose is the study of energetic neutrinos produced in the atmosphere by ultrahigh-energy primary cosmic rays and which subsequently annihilate with atomic electrons in the water detector volume.

In Section 2, I obtain and numerically evaluate production cross sections. Section 3 summarizes the results.

2. CROSS SECTIONS FOR $e^+e^- \to Z^0H^0$ AND $\bar{\nu}_e e^- \to W^-H^0$

Figure 1 is the lowest order Feynman diagram for $e^+e^- \to Z^0H^0$ in the standard model. Neglecting terms of order $q_\mu q_\nu / M_{Z^0}^2$ in the Z^0 propagator, the matrix element gives

$$M = \frac{-e^2 M_{Z^0} \bar{v}(k_2) \gamma^\mu [R_e(1+\gamma_5) + L_e(1-\gamma_5)] u(k_1) \varepsilon^\mu(p_1)}{4 \sin\theta_W \cos\theta_W \, (s - M_{Z^0}^2)^2} \tag{4}$$

Evaluating the traces, we obtain

$$|\bar{M}|^2 = \frac{e^4 M_{Z^0}^2 (8X_W^2 - 4X_W + 1)}{8X_W^2 (1 - x_W)^2 (s - M_{Z^0}^2)^2} \left[k_1 \cdot k_2 + 2 \frac{(k_1 \cdot p_1)(k_2 \cdot p_1)}{M_{Z^0}^2} \right] \tag{5}$$

where use has been made of

$$R_e = 2X_W \equiv 2 \sin^2 \theta_W, \qquad L_e = 2X_W - 1$$

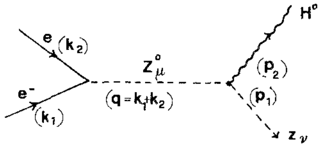

Fig. 1. Lowest order Feynman diagram for $e^+e^- \to Z^0H^0$ in the standard model.

Let us introduce the following Mandelstam invariants,

$$
\begin{aligned}
s &= (k_1+k_2)^2 = (p_1+p_2)^2 \\
u &= (p_2-k_2)^2 = (p_1-k_1)^2 \\
t &= (p_1-k_2)^2 = (p_2-p_1)^2
\end{aligned}
\tag{6}
$$

and specify the momenta of the incident and emerging particles in the CM frame:

$$
\begin{aligned}
k_1 &= (k;\, 0, 0, -k) \\
k_2 &= (k;\, 0, 0, k) \\
p_1 &= (E'_1;\, p\sin\theta, 0, p\cos\theta) \\
p_2 &= (E'_2;\, -p\sin\theta, 0, -p\cos\theta)
\end{aligned}
\tag{7}
$$

with

$$k = |\mathbf{k}|, \qquad p = |\mathbf{p}_1| = |\mathbf{p}_2|$$

$$
\begin{aligned}
E'_1 &= \frac{1}{2\sqrt{s}}(s + M^2_{Z^0} - M^2_{H^0}) \\
E'_2 &= \frac{1}{2\sqrt{s}}(s - M^2_{Z^0} + m^2_{H^0}) \\
p &= \frac{1}{2\sqrt{s}}[(s - M^2_{H^0} - M^2_{Z^0})^2 - 4m^2_{H^0}M^2_{Z^0}]^{1/2}
\end{aligned}
\tag{8}
$$

where p is the value of the CM momentum of the emerging Higgs boson or the intermediate neutral gauge boson. The total cross section gives

$$\sigma(e^+e^- \to Z^0H^0) = \frac{G_F^2 M^4_{Z^0}(8X^2_W - 4x_W + 1)p(3M^2_{Z^0} + p^2)}{6\pi\sqrt{s}(s - M^2_{Z^0})^2} \tag{9}$$

From (8), equation (9) becomes

$$
\begin{aligned}
\sigma = {} & \frac{G_F^2 M^4_{Z^0}(8x^2_W - 4x_W + 1)}{48\pi s^2(s - M^2_{Z^0})^2}[(s - M^2_{H^0} - M^2_{Z^0})^2 - 4M^2_{H^0}M^2_{Z^0}]^{1/2} \\
& \times [12sM_{Z^0} + (s - m^2_{H^0} - M^2_{Z^0}) - 4m^2_{H^0}M^2_{Z^0}]
\end{aligned}
\tag{10}
$$

2.1. The Process $\bar{\nu}_e e^- \rightarrow W^- H^0$

The Feynman diagram of this process is given in Figure 2. Once again, neglecting terms of order $q_\mu q_\nu / M_W^2$ in the W propagator, the matrix element gives

$$M = iG_{v\text{-}A} \cdot g_{WWH^0} \bar{v}(k_2) \gamma^\mu (1 - \gamma_5) u(k_1) \varepsilon^\mu (p_1) \tag{11}$$

with

$$G_{v\text{-}A} = \left(\frac{G_F M_W^2}{+\sqrt{2}} \right)^{1/2}, \qquad g_{WWH^0} = 2M_W^2 (G_F \sqrt{2})^{1/2}$$

as couplings and $\varepsilon^\mu(p_1)$ is the W-polarization four-vector,

$$|\bar{M}|^2 = 2G_{v\text{-}A}^2 g_{WWH^0}^2 \left[k_1 \cdot k_2 + \frac{2(p_1 \cdot k_1)(p_1 \cdot k_2)}{M_W^2} \right] \tag{12}$$

The total cross section follows readily from (8) and (12):

$$\begin{aligned} &\sigma(\bar{\nu}_e e^- \rightarrow W^- H^0) \\ &= \frac{G_F^2 M_W^4}{24 \pi s^2 (s - M_W^2)^2} [(s - m_{H^0}^2 - M_W^2)^2 - 4m_{H^0}^2 M_W^2]^{1/2} \\ &\quad \times [12 M_W^2 s + (s - m_{H^0}^2 - M_W^2)^2 - 4m_{H^0}^2 M_W^2)] \end{aligned} \tag{13}$$

and differs from (10) just by replacing M_{Z^0} by M_W and changing the coupling constants.

2.2. Numerical Estimates of Cross Sections

We now evaluate (10) and (13) numerically using the following input data:

$$G_F^2 = 5.29 \times 10^{-38} \text{ cm}^2/\text{GeV}; \qquad M_W = 81.8 \pm 3.6 \text{ (UA1/UA2)}$$

$$M_{Z^0} \approx 93.3 \pm 2.7 \text{ (UA1/UA2)}; \qquad x_W = 0.221 \text{ (UA1/UA2)}$$

The numerical results for the cross sections are presented in Tables I and II. The cross sections (10) versus the CM energy $\sqrt{S}$, for fixed m_{H^0}, are plotted in Figure 3 [the cross sections (13) versus $\sqrt{S}$ have the same shapes, with the sizes differing by small amounts].

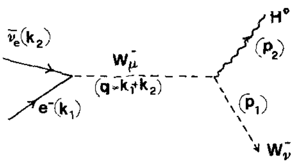

Fig. 2. Lowest order Feynman diagram for $\bar{\nu}_e e^- \rightarrow W^- H^0$ in the standard model.

Table I. Maximum Production Cross Sections for $e^+e^- \rightarrow Z^0H^0$ As a Function of the CM Energy $\sqrt{S}$ and for Fixed Light Higgs Boson Masses

$\sqrt{S}$	$\sigma\,(nb)$									
(GeV)	$m_{H^0}=7$	$m_{H^0}=15$	$m_{H^0}=25$	$m_{H^0}=30$	$m_{H^0}=40$	$m_{H^0}=50$	$m_{H^0}=60$	$m_{H^0}=75$	$m_{H^0}=80$	$m_{H^0}=100$
105	4.4×10^{-2}									
115		5.29×10^{-2}								
125			1.87×10^{-2}							
130				1.37×10^{-2}						
145					8.12×10^{-3}					
155						5.2×10^{-3}				
165							3.58×10^{-3}			
175								1.36×10^{-3}		
190									8.1×10^{-4}	
215										4.74×10^{-4}

Table II. Maximum Production Cross Sections for $\bar{\nu}_e e^- \rightarrow W^- H^0$ As a Function of the CM Energy and for Fixed Light Higgs Boson Masses

$\sqrt{S}$ (GeV)	σ (nb)									
	$m_{H^0}=7$	$m_{H^0}=15$	$m_{H^0}=25$	$m_{H^0}=30$	$m_{H^0}=40$	$m_{H^0}=50$	$m_{H^0}=60$	$m_{H^0}=75$	$m_{H^0}=80$	$m_{H^0}=100$
90	1.5×10^{-1}									
101		5.4×10^{-2}								
115			1.94×10^{-2}							
120				1.42×10^{-2}						
132					8.23×10^{-3}					
140						5.5×10^{-3}				
155							3.6×10^{-3}			
170								2.1×10^{-3}		
180									1.78×10^{-3}	
201										1.52×10^{-3}

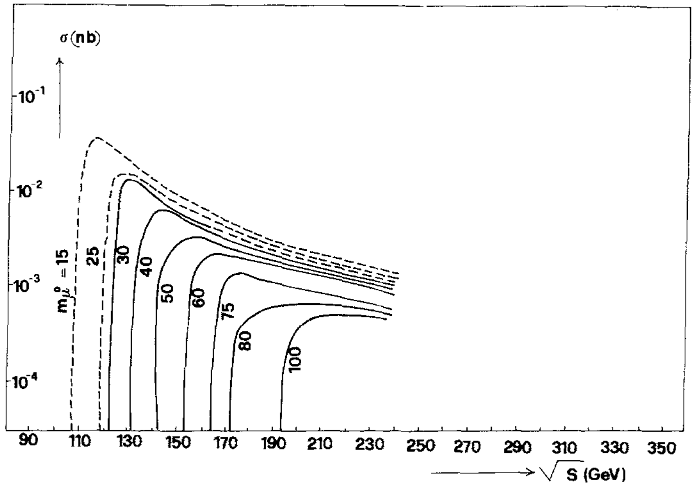

Fig. 3. $\sigma(e^+e^- \to Z^0H^0)$ versus $\sqrt{S}$ for fixed values of m_{H^0}.

3. SUMMARY

I have calculated production cross sections of the light Higgs boson H^0 ($m_{H^0} < 100\ \mathrm{GeV}/c^2$) in association with the neutral gauge boson Z^0, via the process

$$e^+e^- \to Z^0H^0$$

with improved CM energies of up to 0.1-0.2 TeV or more, expected to be available to the next generation of electron-positron colliders, such as LEP III and VLEEP. By way of analogy with the e^+e^--collider mode of associated production (of light Higgs bosons), I have also presented data on the production of the Higgs particles in a parallel reaction:

$$\bar{\nu}_e e^- \to W^- H^0$$

which requires ultrahigh-energy neutrinos, of the order of laboratory energy $E_{\bar{\nu}} \sim 10^{16}$ eV, for a 100 GeV/c^2 boson mass.

The following emerges from the numerical data, as presented in Tables I and II and in Figure 3.

In both processes, and for each light Higgs boson mass considered, maximum cross section is attained at a value of the CM energy quite close to the threshold value. This behavior appears to optimize in a remarkable way the overall CM energy requirement of LEP II, thereby enabling "light" Higgs boson mass spectrum of interest ($7 < m_{H^0} < 100\ \mathrm{GeV}/c^2$) to fall within the range of the exploration capability ascribed to LEP II. In both processes, too, maximum cross sections with m_{H^0} up to 75 GeV/c^2 or so appear somewhat more sizable in comparison with those for the production of massive Higgs bosons in proton-(anti)proton colliders at multi-TeV CM energies, via the gluon-fusion mechanism ($gg \rightarrow H^0$) and Higgs boson formation by a pair of virtual gauge bosons [$q\bar{q} \rightarrow W^*(Z^{0*})H^0$] (Cahn and Dawson, 1984). This apparent marginality of the equality of production cross sections for light and massive Higgs scalar bosons in the e^+e^- collider at LEP II and in the pp ($\bar{p}p$) supercollider, respectively, may suggest that the physics capabilities of the next generation of electron-positron and proton-(anti)proton options are both attractive and somewhat complementary, and that both categories of accelerators may prove equally relevant for future searches for a Higgs boson in the widest possible mass spectrum of interest. However, bringing the experimental backgrounds, which are known to be fiercer at the hadron colliders than at their e^+e^- counterparts, into the picture will most probably tilt the balance in favor of LEP II as a more likely machnine to detect a Higgs boson.

Finally, although the $\bar{\nu}_e e^-$ mode of light Higgs boson production yields slightly larger cross sections for the same Higgs boson masses and at lower CM energies when compared with the electron-positron mode of production, it may not be easily accessible, experimentally, as truly enormous neutrino energies are required ($E_\nu > 10^{16}$ eV for a 100-GeV/c^2 boson mass). That takes one into the realm of cosmic rays, where such energetic neutrinos are indeed expected to be found. Nevertheless, the computed data on production cross sections could be relevant for the project DUMAND, whose purpose is the study of such ultraenergetic neutrinos.

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