Possible means of detecting the Higgs boson in e^+e^- annihilation

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We consider the process $e^+e^- \to \mu^+\mu^-$ + anything for the detection of the Higgs particle as a spike in the missing-mass plot. In an energy range near the Z mass, we find the signal to be reasonably large and the background to be relatively small, if the mass of the Higgs boson is less than about 20 GeV, and a large cut in the effective dimuon mass is applied.

I. INTRODUCTION

In the Weinberg-Salam model[1] of the weak and electromagnetic interactions, the existence of at least one physical Higgs boson is unavoidable. It is, therefore, extremely important to know how such a particle can be detected experimentally. If we assume that there is exactly one such Higgs boson,[2] then it must be electrically neutral, and its coupling to a fermion ψ of mass m_ψ is given by $2^{1/4}G_F^{1/2}m_\psi$, where $G_F = 1.18\times10^{-5}$ GeV^{-2} is the Fermi weak coupling constant. Hence it is both difficult to produce and to detect. Nevertheless, there have been many suggestions[3-12] as to how such a feat may be accomplished. In this paper, we follow a suggestion first given in Ref. 5, and show quantitatively how it may very well be the best hope for finding the Higgs boson experimentally in the not-too-distant future. The process we have in mind is $e^+e^- \to \mu^+\mu^-H$, where we detect only the muons. The Higgs boson H may then appear as a spike in the missing-mass plot, *provided that the background contributions to* $e^+e^- \to \mu^+\mu^-$ + *anything are small enough.*

In Sec. II, we calculate the cross section for $e^+e^- \to \mu^+\mu^-H$ in the Weinberg-Salam model, as a function of energy, the Higgs-boson mass, and the effective dimuon mass. We show that for a range of energies near the Z mass, the counting rate is indeed reasonably large. In Sec. III, we calculate the background contributions to $e^+e^- \to \mu^+\mu^-$ + anything, which are mainly due to $e^+e^- \to \mu^+\mu^-e^+e^-$, or $e^+e^- \to f\bar{f} \to \mu^+\mu^-$ + anything, where f is a heavy quark or a heavy lepton. We show that for a large minimum cut in the dimuon mass, the background can be greatly suppressed with respect to the signal, and the Higgs boson can be detected if its mass is less than about 20 GeV. Finally in Sec. IV, there are some concluding remarks.

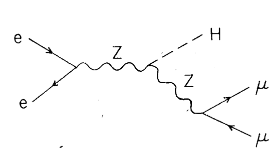

FIG. 1. Dominant contribution to $e^+e^- \to \mu^+\mu^-H$.

II. CROSS SECTION FOR $e^+e^- \to \mu^+\mu^-H$

The dominant contribution to $e^+e^- \to \mu^+\mu^-H$ in the Weinberg-Salam model is via a Z boson in the direct channel, as shown in Fig. 1. Let ω be the energy of the Higgs boson H, and m_H its mass, then the invariant dimuon mass $m_{\mu\mu}$ is given by

$$m_{\mu\mu}^2 = s + m_H^2 - 2\sqrt{s}\,\omega\,, \qquad (2.1)$$

where $\sqrt{s}$ is the total center-of-mass energy. As a function of $m_{\mu\mu}^2/s = x$, the differential cross section is then given by

$$\frac{d\sigma}{dx} = \frac{G_F^3 M_Z^8(1-4\sin^2\theta_W + 8\sin^4\theta_W)^2}{9\sqrt{2}\,(4\pi)^3[(s-M_Z^2)^2+\Gamma_Z^2M_Z^2]} \times \frac{[x^2-2(1+m_H^2/s)x+(1-m_H^2/s)^2]^{1/2}}{(x-M_Z^2/s)^2+\Gamma_Z^2M_Z^2/s^2} \times [x^2+(10-m_H^2/s)x+(1-m_H^2/s)^2]\,, \qquad (2.2)$$

where M_Z and Γ_Z are the mass and the width of the Z boson, and θ_W is the Weinberg angle. In addi-

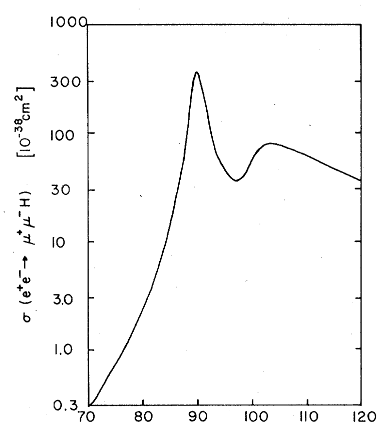

FIG. 2. Total cross section for $e^+e^- \to \mu^+\mu^-H$ is plotted as a function of the total center-of-mass energy $\sqrt{s}$. The mass of the Higgs boson is taken to be 10 GeV.

tion, m_e and m_μ have been neglected relative to $\sqrt{s}$, and x ranges from 0 to $(1-m_H/\sqrt{s})^2$.

The integrated cross section σ as a function of $\sqrt{s}$ is shown in Fig. 2. The various numerical values chosen for this plot are $\sin^2\theta_W=0.22$, $M_Z=90$ GeV, $\Gamma_Z=2.6$ GeV, and $m_H=10$ GeV. It is seen that above 85 GeV or so, σ becomes greater than 10^{-37} cm^2, so it should become measurable if the machine luminosity is not much less than 10^{32} cm^{-2} sec^{-1}. It is also interesting to note that the cross section for producing a HZ pair above threshold, multiplied by the branching ratio of $Z\to\mu^+\mu^-$, is not greater than that for just the Z, multiplied by its branching ratio into $\mu^+\mu^-H$. This means that it may not be necessary to go beyond the HZ threshold in energy for the observation of the Higgs boson, if its mass is less than about 20 GeV.

In Fig. 3, we plot $d\sigma/dx$ as a function of x for $\sqrt{s}=M_Z=90$ GeV and for $\sqrt{s}=110$ GeV. The Z resonance is clearly visible in the latter, with its position given by $x=M_Z^2/s=0.67$. However, the integrated cross section is certainly much greater at 90 GeV, even if only those events with $x>0.5$ are to be counted. This cut in x will be crucial in eliminating most of the background events, since their number is a rapidly decreasing function of x, as will be shown in the next section.

III. BACKGROUND CONTRIBUTIONS TO $e^+e^-\to\mu^+\mu^-$ + ANYTHING

Any e^+e^- process which produces a $\mu^+\mu^-$ pair is a potential source of background. The simplest two processes $e^+e^-\to\mu^+\mu^-$ and $e^+e^-\to\mu^+\mu^-\gamma$ are easily eliminated because the missing mass in either case is zero. Of the other processes, the main two contributions to the background are from[12] $e^+e^-\to\mu^+\mu^-e^+e^-$ and $e^+e^-\to f\bar{f}\to\mu^+\mu^-$ + anything, where f is either a heavy quark or a heavy lepton. These are discussed in turn in the following.

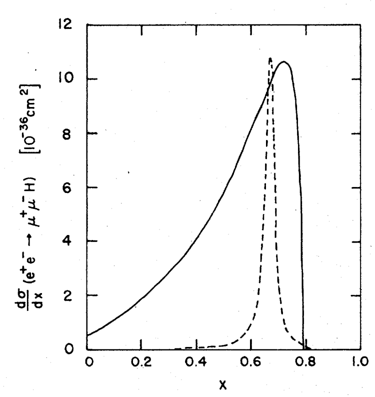

FIG. 3. The differential cross section $d\sigma/dx$ for $e^+e^-\to\mu^+\mu^-H$ is plotted as a function of $x=m_{\mu\mu}^2/s$, at $\sqrt{s}=90$ GeV (solid curve) and at $\sqrt{s}=110$ GeV (dashed curve).

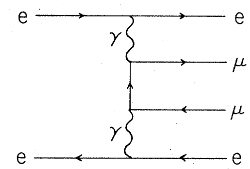

FIG. 4. Dominant contribution to $e^+e^-\to\mu^+\mu^-e^+e^-$.

The process $e^+e^-\to\mu^+\mu^-e^+e^-$ receives its dominant contribution from the collision of two photons,[13] as shown in Fig. 4. The total cross section is given by[13]

$$\sigma(e^+e^-\to\mu^+\mu^-e^+e^-)=\frac{28\alpha^4}{27\pi m_\mu^2}\left(\ln\frac{s}{4m_e^2}\right)\ln\frac{s}{4m_\mu^2}, \tag{3.1}$$

where α is of course the fine-structure constant. At $\sqrt{s}=M_Z=90$ GeV, σ is equal to 2×10^{-31} cm^2, which is larger than $\sigma(e^+e^-\to\mu^+\mu^-H)$ by 5 orders of magnitude. It would, therefore, be impossible to identify the signal if all such background events were to be accepted. However, almost all of these events can be rejected if we make a sufficiently large minimum cut in $x=m_{\mu\mu}^2/s$. The cross section would then become

$$\sigma'\simeq\frac{112\alpha^4}{27\pi s}\left(\ln\frac{s}{4m_e^2}\right)^2\left(\frac{1}{x}\ln\frac{1}{x}\right), \tag{3.2}$$

which, for $x=0.5$, is only 1.3×10^{-37} cm^2 at $\sqrt{s}=M_Z=90$ GeV. On the other hand, the effect of this cut in x only reduces the signal by about one-third, as can be deduced from Fig. 3. Therefore, the Higgs boson would certainly stand out in the missing-mass plot, as far as this source of background is concerned.

The other main source of background is from $e^+e^-\to f\bar{f}$, where f is a heavy quark or a heavy lepton which subsequently decays into a muon. In the Weinberg-Salam model, the total cross section for $e^+e^-\to f\bar{f}$ is given by

$$\sigma(e^+e^-\to f\bar{f})=\frac{4\pi\alpha^2Q^2}{3s}\left(1-\frac{4m_f^2}{s}\right)^{1/2}\left(A+\frac{Bm_f^2}{s}\right), \tag{3.3}$$

where

$$A=1+\frac{(1-4x_W+8x_W^2)(I_3^2-2QI_3x_W+2Q^2x_W^2)}{16Q^2x_W^2(1-x_W)^2[(1-M_Z^2/s)^2+\Gamma_Z^2M_Z^2/s^2]}-\frac{(-1+4x_W)(I_3-2Qx_W)(1-M_Z^2/s)}{4Qx_W(1-x_W)[(1-M_Z^2/s)^2+\Gamma_Z^2M_Z^2/s^2]}, \tag{3.4}$$

and

$$B=2A-\frac{3I_3^2(1-4x_W+8x_W^2)}{16Q^2x_W^2(1-x_W)^2[(1-M_Z^2/s)^2+\Gamma_Z^2M_Z^2/s^2]}, \tag{3.5}$$

with Q the electric charge of f, I_3 the third component of its weak isospin, and $x_W=\sin^2\theta_W$.

Consider as an example the τ lepton, with $Q=-1$, $I_3=-\frac{1}{2}$, and $m_\tau=1.8$ GeV. In Fig. 5, we plot $\sigma(e^+e^-\to\tau^+\tau^-)$ as a function of $\sqrt{s}$. In the energy range near M_Z, the electromagnetic contribution is in fact negligible, and at $\sqrt{s}=M_Z$, we have

$$\frac{\sigma(e^+e^-\to\mu^+\mu^-H)}{\sigma(e^+e^-\to\tau^+\tau^-)}=2\times10^{-3}, \tag{3.6}$$

where $m_H=10$ GeV has been used.[14] Since the branching ratio of $\tau\to\mu$ is about 17%, the number of $\mu^+\mu^-$ pairs from the decay of $\tau^+\tau^-$ will be about 15 times larger than that associated with a Higgs boson. However, we have not taken into account the cut in $x=m_{\mu\mu}^2/s$, which is expected to reduce the background substantially.

To calculate the dependence of $e^+e^-\to\tau^+\tau^-\to\mu^+\mu^-$ + anything on the cut in x, we have to calculate first the decay distribution of $\tau\to\mu\nu\bar{\nu}$ in the e^+e^- center of mass.[15] Neglecting m_τ relative to $\sqrt{s}$, and defining $y=2E_\mu/\sqrt{s}$, we find

$$\frac{d\Gamma}{\Gamma}=\tfrac{1}{3}(1-y)(5+5y-4y^2), \tag{3.7}$$

in agreement with Eq. (1.9) of Ref. 15. Let $y_\pm=2E_{\mu\pm}/\sqrt{s}$; then because the muons are emitted in opposite directions,

$$y_+y_-=4E_{\mu+}E_{\mu-}/s=m_{\mu\mu}^2/s=x. \tag{3.8}$$

Applying the cut $y_+y_->x_0$, we find

$$\int\frac{d\Gamma_+d\Gamma_-}{\Gamma_+\Gamma_-}=1+\tfrac{20}{27}x_0-\tfrac{47}{27}x_0^4+\tfrac{1}{9}(25+27x_0^2+4x_0^3)x_0\ln x_0, \tag{3.9}$$

which shows that for $x_0=0.5$, only 2% of the dimuon events will remain, thus greatly improving the signal-to-noise ratio. It is also possible to compute exactly the dependence of the above background on the missing mass, which is given by $m_-^2=s(1-y_+)(1-y_-)$. Let $z=m_-^2/s$, then for $y_+y_->x_0$ we find

$$\frac{d\Gamma_+d\Gamma_-}{\Gamma_+\Gamma_-}=z\,dz\left\{\tfrac{4}{3}(1+2x_0-4z)[(1+x_0-z)^2-4x_0]^{1/2}+\left(4+z+\tfrac{16}{9}z^2\right)\ln\frac{1-x_0+z+[(1+x_0-z)^2-4x_0]^{1/2}}{1-x_0+z-[(1+x_0-z)^2-4x_0]^{1/2}}\right\}, \tag{3.10}$$

where z ranges from 1 to $(1-\sqrt{x_0})^2$. As a function of z, the Higgs boson will, of course, appear as a bump at $z=m_H^2/s$.

In addition to the τ lepton, the production of the c, b, and t quarks is also expected to contribute significantly to the dimuon background. Whereas the decay distribution of $b\to\mu$ is identical to that of $\tau\to\mu$, the $c\to\mu$ and $t\to\mu$ distributions are given by

$$\frac{d\Gamma}{\Gamma}=2(1-y)^2(1+2y), \tag{3.11}$$

which results in an even greater suppression after the cut in x is applied. Summing over all these contributions, including the factor 3 from the number of colors, we find at $\sqrt{s}=M_Z=90$ GeV a total dimuon background of about 5×10^{-36} cm^2 for $x>0.5$. In the above, we have used the values 0.17, 0.11, 0.14, and 0.12 for the muon branching fractions of the τ, c, b, and t, respectively.[16] We plot in Fig. 6 the dependence of this background on the missing-mass variable z, and superimpose on it the Higgs-boson signal if $m_H=10$ GeV. Thus we have demonstrated clearly the feasibility of such an experiment for the detection of the Higgs boson.

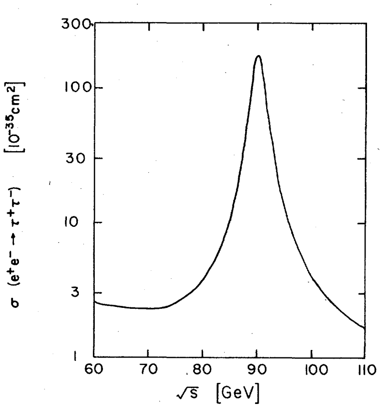

FIG. 5. Total cross section for $e^+e^-\to\tau^+\tau^-$ is plotted as a function of $\sqrt{s}$.

IV. CONCLUDING REMARKS

Since the Higgs boson is both difficult to produce and to detect, it makes sense to think of an experimental situation, where it does not have to be detected through its decay into other particles. The

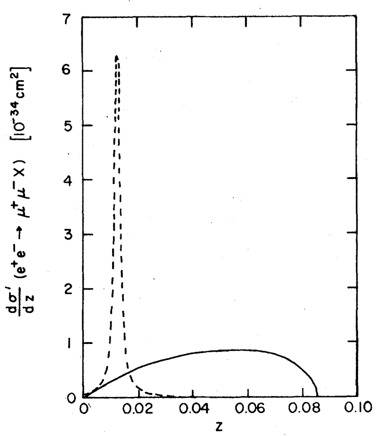

FIG. 6. The differential cross section $d\sigma'/dz$ for $e^+e^- \to \mu^+\mu^-$ + anything is plotted as a function of $z = m_-^2/s$, where m_- is the missing mass, at $\sqrt{s} = M_Z = 90$ GeV. A cut of $x = m_{\mu\mu}^2/s > 0.5$ has been applied. The solid curve denotes the background contribution from τ, c, b, and t decay. The dashed curve represents a Higgs boson of 10 GeV with an experimental resolution of 1 GeV.

process $e^+e^- \to \mu^+\mu^- H$ is exactly such a candidate. Unfortunately, the cross section is too small at PEP and PETRA energies, so the experiment will only become feasible at the proposed LEP machine at CERN. However, once the Z is discovered as a resonance in e^+e^- annihilation, the Higgs boson can also be detected, if its mass is less than about 20 GeV. This upper limit comes about because the cut in x, which is needed to suppress the background, also limits the maximum value of m_H to be $\sqrt{s}\,[1 - (x_{\min})^{1/2}]$, at which point the signal vanishes.

Once the Higgs-boson signal is clearly established, then one can examine its decay products by going back to the corresponding dimuon events and looking at their accompanying particles. At an e^+e^- luminosity of 10^{32} cm^{-2} sec^{-1}, one can obtain 20 such events per day at $\sqrt{s} = M_Z = 90$ GeV, for $m_H = 10$ GeV. Thus one can analyze the decay modes of the Higgs boson all at once, including those with one or more missing particles, such as a neutrino or a neutral kaon.

If both H and Z are produced in e^+e^- annihilation, then H can be detected either by its decay into two or more identifiable particles, or by its recoil against the Z, in which case the Z itself has to be identified. If $Z \to \mu^+\mu^-$ is used as the signature, then as Fig. 2 and Fig. 3 show, the cross section above the HZ threshold is actually smaller than what it is at the Z resonance. If $H \to \mu^+\mu^-$ is used as the signature, then since the branching fraction of $H \to \mu^+\mu^-$ is expected to be smaller than that of $Z \to \mu^+\mu^-$, the situation is worse. Therefore, it is actually better to look for the Higgs boson at the Z resonance than to find it in associated production, if its mass is less than about 20 GeV.

After the completion of this paper, we received two reports[17] dealing with the same subject matter. However, only in our paper is a detailed discussion of the background given, without which the practical importance of the $Z \to H\mu^+\mu^-$ decay cannot be established.

ACKNOWLEDGMENT

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