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H° AT A 300 GeV e^+e^- COLLIDER*

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ABSTRACT

In the mass range from 80–180 GeV, no simple strategy for a detection of the H° presently exists. Here we investigate the reaction $e^+e^- \rightarrow H^\circ Z^\circ$ at a center-of-mass energy of 300 GeV. We calculate the necessary luminosity to observe the H° in the missing mass distribution of the $Z^\circ \rightarrow l^+l^-$. It is shown that even for the case $M_{Z^\circ} = M_{H^\circ}$, a clear signal can be established.

Possibilities for realizing an e^+e^- collider with sufficient luminosity at such energies are investigated. In particular, the possibility of colliding an electron linear accelerator with a positron storage ring is discussed.

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INTRODUCTION

One of the most important goals of future experiments in particle physics is to clarify the mechanism of electroweak symmetry breaking. In the standard electroweak theory the symmetry breaking mechanism predicts at least one elementary neutral Higgs boson (H°).[1)]

The potential to detect the H° in the standard electroweak theory has the role of a benchmark reaction for future high energy collider projects. There are no precise predictions for the mass of the Higgs (M_{H°) within the standard model, and M_{H° can have any value from a few GeV — the present experimental limit — up to a few TeV, where the couplings become very strong. It is therefore important that search strategies for the H° cover as much of this potential mass range as possible.

Strategies for detecting the H° and investigating the symmetry breaking mechanism are a central focal point of the two future high energy hadron colliders, SSC and LHC.[2,3)] For Higgs masses above the threshold for decaying into vector bosons, a convincing search strategy for the H° exists. The H° is expected to be copiously produced via vector boson or gluon fusion[4,5)] and has a large branching ratio into vector bosons. In particular, the decay $H^\circ \rightarrow Z^\circ\, Z^\circ \rightarrow l^+l^-l^+l^-$, where l^+l^-stands for the decay of the Z° into electrons or muons, seems to be a gold-plated mode for the SSC and LHC.

Below the two weak vector boson threshold the situation looks more difficult because no clean, detectable signal exists.[6)] In this mass range the H° is expected to decay mainly into the heaviest fermion pair (most likely $H^\circ \rightarrow b\bar{b}$). Although the event rate is high, the signal has to compete with an enormous background from ordinary hadronic interactions. Rare decay modes like $H^\circ \rightarrow Z^\circ\, Z^{\circ\star}$ and $H^\circ \rightarrow \gamma\gamma$ offer potentially clean signatures, but the branching ratios are tiny. Therefore, at a future hadron collider no distinct signal, which is as convincing as the signature $H^\circ \rightarrow Z^\circ\, Z^\circ \rightarrow l^+l^-l^+l^-$, exists for H° masses below the weak vector boson threshold.

Given this situation it seems worthwhile to look into other alternatives. One obvious alternative is e^+e^- collisions; and indeed existing e^+e^- collider projects will be sensitive to the H° up to the weak vector boson mass. At the Z° peak, SLC and LEP will be able to detect a H° up to about 40 GeV. LEP2 will be sensitive up to 80 GeV.7) In both cases the basic reaction, $e^+e^- \rightarrow Z^\circ H^\circ$, offers a clean signature in the missing mass distribution calculated from the decay $Z^\circ \rightarrow l^+l^-$.8,9) Higgs production has been studied in connection with the high energy e^+e^- linear collider. At high energies W–fusion is the main production mechanism for the H° in e^+e^- collision similar to pp-collision and above the weak vector boson threshold, a simple signature exists by directly reconstructing the Higgs particle mass out of the observed vector bosons.3,10) Below the threshold, for the decay into two weak vector bosons, the situation is less straightforward. A direct reconstruction of the decay $H^\circ \rightarrow b\bar{b}$ has to compete with large background contributions. A luminosity above 10^{33}cm^{-2} sec is necessary, and it seems almost impossible to unravel a H° with a mass in the vicinity of the vector boson mass by directly reconstructing the decay $H^\circ \rightarrow b\bar{b}$ .11,12)

THE REACTION $\mathbf{e^+e^- \rightarrow Z^\circ H^\circ}$

We consider here, what energy and luminosity extensions compared to LEP2 are necessary to cover the gap between LEP2 and a future pp-collider with the reaction $e^+e^- \rightarrow Z^\circ H^\circ$.

This reaction has been calculated by Bjorken8) at the Z° peak, and by Lee9) above the Z° . The total cross section above the Z° is given by9)

$$\sigma_{tot} = \sigma_{\mu\mu} \frac{a_e^2 + v_e^2}{32\sin^2\theta_w \cos^2\theta_w} \; \frac{p}{\sqrt{s}} \; \frac{s(3M_{Z^\circ}^2 + P^2)}{(s - M_{Z^\circ}^2)^2} \quad ,$$

where $\sigma_{\mu\mu}$ is the pointlike QED cross section for muon pair production. Here a_e and v_e are the axial and vector coupling constants of the initial electrons to the Z° ; $a_e = -1$; $v_e = (4\sin^2\theta_w - 1)$, and P is the three momentum of the H° or Z° .

Figure 1 shows the cross section in the reaction $e^+e^- \rightarrow Z^\circ H^\circ$ for different Higgs masses as a function of the center-of-mass energy. At 300 GeV the cross section is about 0.1 pb. The cleanest detection mode, $Z^\circ \rightarrow l^+l^-$, has a branching ratio of 7%; therefore, after appropriate cuts, we expect about 20 events for a luminosity of 5000 $pb^{-1}$and a Higgs mass of 180 GeV. The reaction $e^+e^- \rightarrow Z^\circ H^\circ$ with subsequent decay $Z^\circ \rightarrow l^+l^-$ can be considered the gold-plated detection mode in e^+e^- collisions.

Well above the kinematic threshold the cross section will decrease as $1/s$ similar to $\sigma_{\mu\mu}$ and will be about 20% of $\sigma_{\mu\mu}$. In contrast, the above-mentioned process of vector boson fusion is expected to increase logarithmically with s and at high energies will eventually dominate. Nevertheless, for Higgs masses in the here considered mass range the cross section in the distinct mode $e^+e^- \rightarrow Z^\circ H^\circ$ at $E_{\text{cm}}=$ 300 GeV is comparable to the H° production cross section via vector boson fusion at collision energies of a TeV.

The main background for the reaction $e^+e^- \rightarrow Z^\circ H^\circ$ is expected to come from the reaction $e^+e^- \rightarrow Z^\circ Z^\circ(\gamma)$. The differential cross section for this reaction has been calculated by Hinchliff[13)]

$$\frac{d\sigma}{d\cos\theta} = \frac{3}{16}\sigma_{\mu\mu} \quad \frac{a_e^4 + v_e^4 + 4v_e^2 a_e^2}{(32\sin^2\theta_w \cos^2\theta_w)^2}\left(1 - \frac{4m_{t^\circ}^2}{s}\right)^{\frac{1}{2}}$$
$$\left\{\frac{u}{t} + \frac{t}{u} + m_{Z^\circ}^2\frac{s}{ut} + m_{Z^\circ}^4\left(\frac{1}{u^2} + \frac{1}{t^2}\right)\right\}$$

Although the cross section is large, it is concentrated at small scattering angles, in contrast to the signal reaction. Figure 2 shows the cross section with cuts applied to the scattering angle. Since the H° will give a narrow peak in the missing mass distribution at M_{H°, a signal will not be confused with the reaction $e^+e^- \rightarrow Z^\circ Z^\circ(\gamma)$ as long as the masses M_{Z° and M_{H° are not too close together. The case $M_{Z^\circ} = M_{H^\circ}$ requires further attention, since both missing mass distributions will be identical in shape. In principal, the H° is narrower than the Z°, but in practice it is difficult to realize a missing mass resolution sharper than the Z° width.

Nevertheless, in this case it is possible to establish an H° signal by considering the different decay branching ratios for the H° and Z° . At these masses the H° is expected to decay almost 100% into $b\bar{b}$ pairs, whereas the decay $Z^\circ \rightarrow b\bar{b}$ has a branching ratio of about 15%. One can look for an excess of $b\bar{b}$ events in the hadronic jets recoiling against $Z^\circ \rightarrow l^+l^-$. This procedure does not depend on the theoretical knowledge of the Z° branching ratios nor the $e^+e^- \rightarrow Z^\circ Z^\circ(\gamma)$ cross section. The Z° branching ratios will be well measured at the Z° peak, and the reaction $e^+e^- \rightarrow Z^\circ Z^\circ(\gamma)$ can be measured simultaneously by using purely leptonic decays (including neutrinos).

At $E_{\text{cm}}=$ 250 GeV and assuming $e^+e^- \rightarrow Z^\circ H^\circ$, and assuming $M_{H^\circ} = 92$ GeV, we expect for $e^+e^- \rightarrow Z^\circ H^\circ$ and $Z^\circ \rightarrow l^+l^-$ a cross section of about 0.02 pb. For the reaction $e^+e^- \rightarrow Z^\circ Z^\circ$ and the requirement that one Z° decays into $b\bar{b}$ and the other Z° into electrons or muons is of similar size if one applies a cut in the scattering angle at $|\cos(\theta)| \leq 0.7$. Therefore, we are left with about 100 events signal and 100 events background before criteria have to be applied to separate the decay $Z^\circ \rightarrow b\bar{b}$ from $Z^\circ \rightarrow q\bar{q}$ in the reaction $e^+e^- \rightarrow Z^\circ Z^\circ(\gamma)$. Even with $b\bar{b}$-tagging efficiency of 30%, a H° could be established in the special case of $M_{Z^\circ} = M_{H^\circ}$. A tagging efficiency for $b\bar{b}$ events of 30% seems possible, in particular if one considers the distinct experimental signatures of the b quark (semileptonic decay and the long lifetime) and that 1/4 of all hadronic Z° decays are $Z^\circ \rightarrow b\bar{b}$.

With an e^+e^- collider at $E_{\text{cm}}=$ 300 GeV and an integrated luminosity of 5000 pb^{-1} for the H° the discovery gap up to the threshold of the decay into two vector bosons can be closed with a simple tree level reaction and a clean signature. The H° makes a strong case for an e^+e^- collider with 1.5 times the energy and 10 times the luminosity of LEP2. Such a e^+e^- collider would allow, in addition detailed tests of the $W^\pm$ production dynamics and the compositness scale of quarks, leptons and vector bosons much beyond LEP2 — e.g., about 10^4 top quark pairs and 10^5 $W^\pm$ pairs are produced.

e^+e^- COLLIDER AT 300 GeV

Since e^+e^- storage rings are a successful concept it seems natural to try to extend them up to $E_{\rm cm}$= 300 GeV. Unfortunately, the affordable energy of electron storage rings is severely limited by synchrotron radiation.[14)]

In addition, for storage rings the luminosity is strongly limited by the beam-beam interaction; e.g. the luminosity at LEP2[15)] at $E_{\rm cm}$=190 GeV is expected to be $3 \cdot 10^{31}{\rm cm}^{-2}/{\rm sec}$. The rf power requirements to overcome the synchrotron radiation losses are 16 Megawatts, which makes it difficult to increase the luminosity by enlarging the number of bunches. An e^+e^- storage ring collider in the SSC tunnel at $E_{\rm cm}$= 300 GeV and a luminosity of $5 \cdot 10^{32}$ ${\rm cm}^{-2}/{\rm sec}$ would require an rf power well above 100 MW.

One way out of the problem of synchrotron radiation seems to be the linear collider approach.[16)] In this concept, particle bunches are brought into collision only once. In order to get a sufficiently high luminosity with a reasonable power consumption extremely dense collisions have to be produced. So far the experience with linear colliders is very limited. A TeV linear collider with a luminosity of 10^{33} ${\rm cm}^{-2}/{\rm sec}$ is technically very challenging.[17)]

Initiated by the intermediate mass H° working group in Snowmass 1986,[18)] I started to look into the possibility of a hybrid collider concept.[19)] Here a linear electron accelerator is brought into collision with a positron storage ring. In such a scheme the electrons do not suffer from synchrotron radiation losses and the positron's energy can be kept sufficiently low so as to keep those losses within reasonable bounds. Both energies are decoupled, and $E_{\rm cm}$= 300 GeV can be realized by colliding a 300 GeV electron beam with a stored positron beam of 75 GeV energy.

The electron beam intensity has to be kept sufficiently low so that it does not blow up the stored positron beam. The positron beam has to be very intense in order to achieve a sizeable luminosity. The constraints on the intensities and the spot size of the two beams are explained in more detail in the above-mentioned publication.

Table 1 gives some possible parameters for linear versus storage ring colliders at $E_{\mathrm{cm}}=$ 300 GeV and $E_{\mathrm{cm}}=$ 500 GeV. The effective tunnel radius for the two storage rings correspond roughly to the LEP and SSC cases.

Compared to a linear collider, the requirements on the spot sizes are less demanding and no complex injection and cooling devices are necessary, but in contrast to a linear collider, the hybrid scheme cannot be extended into the TeV range. Both a 300 GeV linear collider and a 300 GeV linac storage ring collider would contain technical elements that need to be mastered for the more ambitious TeV collider.

SUMMARY

The reaction $e^+e^- \rightarrow Z^\circ H^\circ$ at $E_{\mathrm{cm}}=$ 300 GeV can fill an important gap in the search for the standard model H°. A prototype linear collider or a linear against storage ring collider at that energy deserves more detailed consideration.

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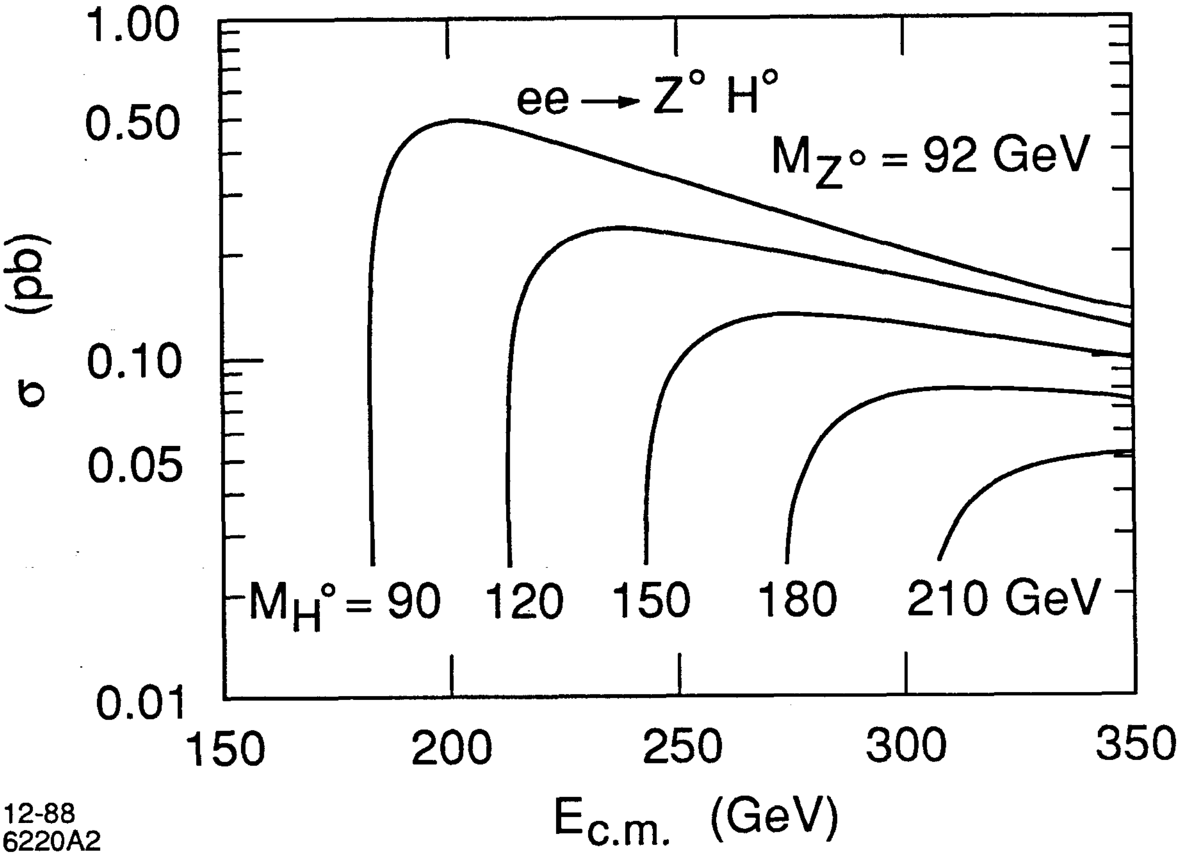
Table 1. Parameter for linear against storage ring e^+e^- colliders of 300 and 500 GeV

Particles	e^-	e^+	e^-	e^+
Energy (GeV)	300.0	75.0	500.0	125.0
E_{cm} (GeV)	300.0		500.0	
Circumf. (km)	–	20.0	–	70.0
coll. rate (KHz)	500		200	
N particle (10^{10})	0.05	20	0.08	20
Power (MW)	11.3	13.9	12.6	12.2
$\sigma_x(\mu m)$	1.0	1.0	1.0	1.0
$\sigma_y(\mu m)$	0.2	0.2	0.2	0.2
σ_z (cm)	–	0.4	–	0.4
Q_x	–	448	–	630
$\delta_{bstr.}$	0.08	0.000	0.14	0.000
Luminosity (cm^2)	$2.8 \cdot 10^{33}$		$2.0 \cdot 10^{33}$	

FIGURE CAPTIONS

1. Total cross section for the reaction $e^+e^- \to Z^\circ H^\circ$ versus the center-of-mass energy for various masses of the neutral Higgs.

2. The cross section for the reaction $e^+e^- \to Z^\circ Z^\circ$versus the center-of-mass energy for scattering angles, cut as indicated.



ee → Z° H°
$M_{Z°}$ = 92 GeV
$M_{H°}$ = 90
120
150
180
210 GeV
σ (pb)
1.00
0.50
0.10
0.05
0.01
150
200
250
300
350
$E_{c.m.}$ (GeV)
12-88
6220A2

Fig. 1

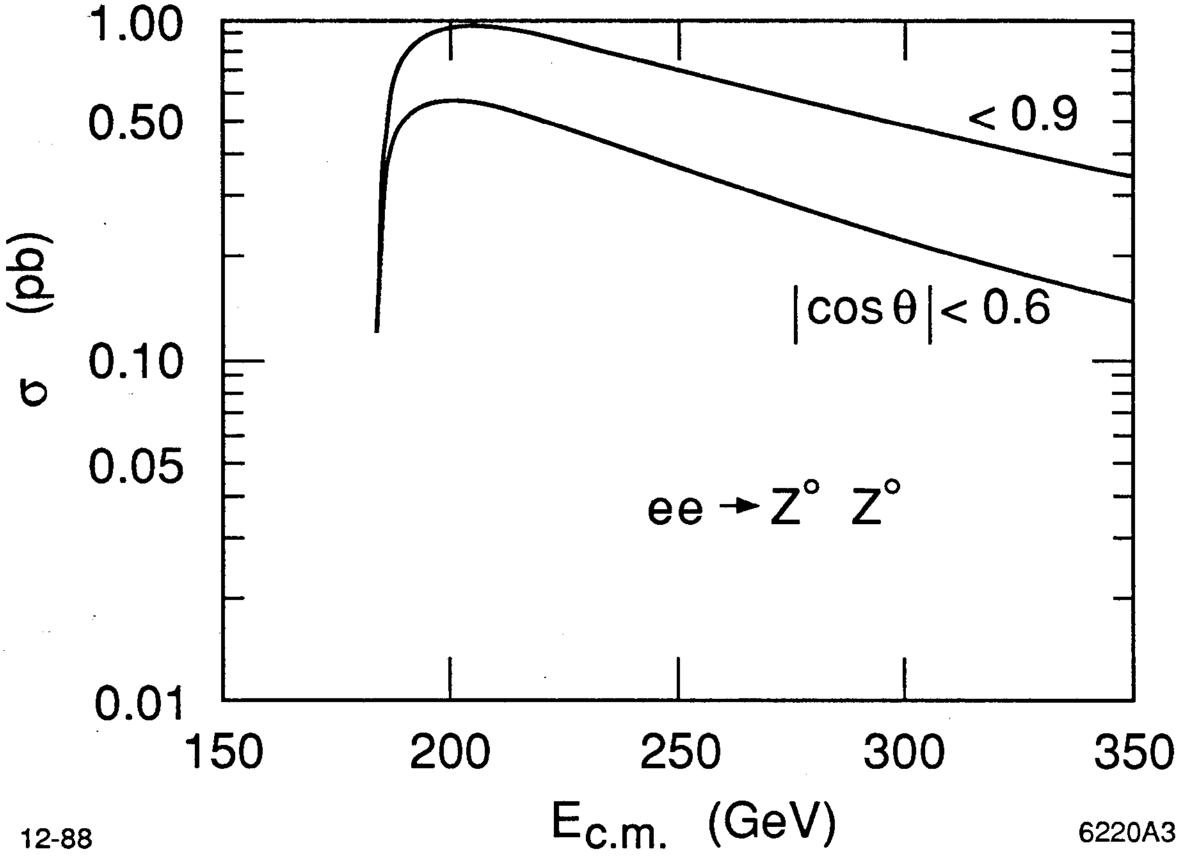

1.00
0.50
0.10
0.05
0.01
σ (pb)
150
200
250
300
350
$E_{c.m.}$ (GeV)
< 0.9
|cos θ| < 0.6
ee → Z° Z°
12-88
6220A3

Fig. 2