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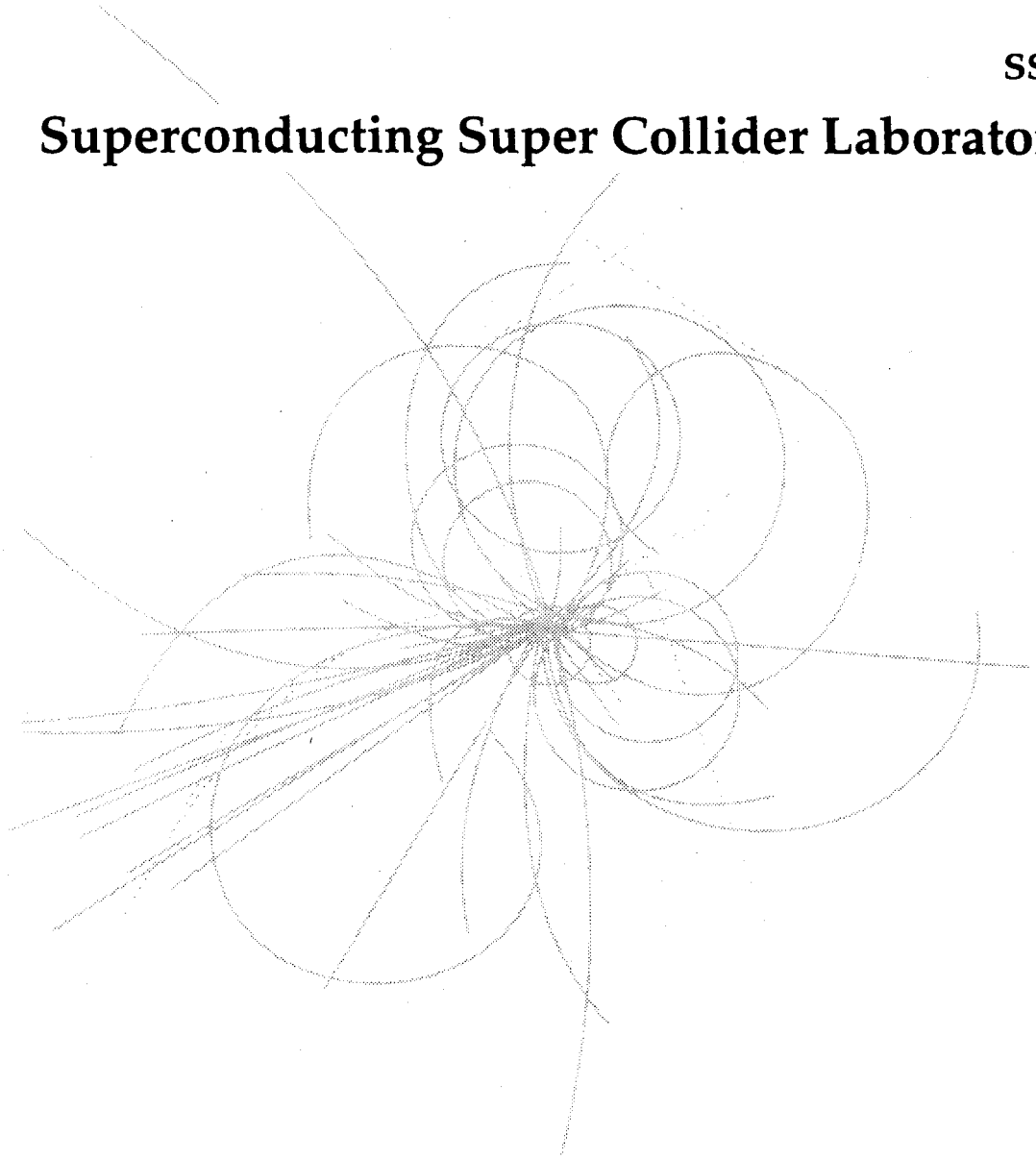

Detecting Invisible Higgs Bosons at the SSC and LHC

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S.G. Frederiksen

Superconducting Super Collider Laboratory*
2550 Beckleymeade Avenue
Dallas, TX 75237

N. Johnson

Physics Department
University of Texas at Dallas
Richardson, TX 75083

G. Kane

Randall Physics Laboratory
University of Michigan
Ann Arbor, MI 48109

J. Reid

Physics Department
University of Tulsa
Tulsa, OK 74104

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Abstract

In some extensions of the Standard Model the (lightest) Higgs boson can have mainly invisible decays, decaying to a pair of the lightest supersymmetric partners, or to Goldstone bosons, or to Majorons, none of which interact in the detector. Thus it is not clear how such a Higgs boson can be detected. We show that associated production of such Higgs bosons with Z's at high-luminosity hadron colliders can provide a detectable signal for the mass region of most interest, $M_h \lesssim 150$ GeV. Associated production with W's can provide confirmation of such a signal. If a Higgs boson is detected another way, so that M_h is known, this method may allow a measurement of branching ratio (BR) $(h \rightarrow invisible)$, and may also allow measurement of other BR.

1.0 INTRODUCTION

An important aspect of why the U.S. particle-physics community has endorsed the Superconducting Super Collider (SSC) as its highest priority is the belief—based on extensive research and several studies—that whatever form nature has chosen for the physics of the Higgs sector can be uncovered by experiments there. In this paper we address one way in which this belief could turn out to be wrong, or at least unproven unless very specialized detectors are built.[1] Namely, it is possible that once the Standard Model is extended, the Higgs boson (or the lightest scalar that mainly plays the role of the Higgs boson if several scalars are present) can dominantly decay into particles that do not interact in the detector such as Goldstone bosons,[1,2] or a pair of the lightest supersymmetric partners,[3] or Majorons,[4] or perhaps other invisible objects. Such a Higgs boson cannot be directly detected, of course. Some theories[5] also have stable scalars that could be detected with the method for which we argue below. Also, the heavier Higgs bosons of supersymmetric models (H^0, A^0) have in general decays to the lightest supersymmetric particle (LSP + LSP) that may be detectable this way; *e.g.*, in the models of Reference 6, H^0, A^0 decay about 20% of the time this way.

We will see below that such invisible Higgs bosons can be discovered at the SSC using the associated production mode $pp \to Z + h + anything$, with $Z \to e^+e^-$ or $\mu^+\mu^-$, and *invisible* h. For most of the mass region of interest, detection is also possible at the Large Hadron Collider (LHC). It is appropriate to consider production via $q + \bar{q} \to Z^* \to Z + h$, since we assume that the Higgs mechanism is responsible for generating the mass of the gauge bosons; thus the ZZh and WWh couplings will be full-strength or nearly so. That also defines the mass region of interest for our analysis, since once M_h exceeds approximately 150 GeV the decays $h \to ZZ$ and/or $h \to WW$ will have large enough branching ratios to be detectable even if they are not full-strength. In a supersymmetric world this situation holds, and there is also an effective upper limit well below 2 M_Z on the mass of the lightest scalar, not only in the minimal supersymmetric Standard Model where the upper limit is about 140 GeV (for large M_Z), but in general supersymmetric theories as well.[7]

Thus the important question is whether an invisible Higgs boson of mass below about 150 GeV can be detected in associated production with Z *or* W. At the Large Electron-Positron Collider (LEP) the same technique can be used, of course, to search up to M_h values somewhere between 80 GeV and M_Z or even higher depending on the energy and integrated luminosity. So for the hadron colliders the region 80 GeV $\lesssim M_h \lesssim$ 150 GeV is the interesting one.

Detection of a normal Higgs boson h decaying in the $\bar{b}b$ mode in associated production with a Z or W is not considered a favored approach for discovery. That is because of the large QCD background present in the Z-(or W) plus-2-jet state. For our purposes only leptonic decays of the Z (and W) plus missing momentum are used (not including τ decays). The dominant background (irreducible) comes from the electroweak process $q+\bar{q} \to Z+Z$, followed by one $Z \to e^+e^-$ or $\mu^+\mu^-$ and the other $Z \to \nu\bar{\nu}$. This has a $\sigma \times BR$ about the same size as that for our process ($Z + h$ with $Z \to e^+e^-$ or $\mu^+\mu^-$, *invisible* h). If $\sigma(Z + Z)$ were not separately normalized to high precision by the measurement where both Z's decay to leptons, it would not be possible to detect $Z + \textit{invisible } h$. But because $\sigma(Z + Z)$ will be measured accurately after some time at the hadron colliders, detection of $Z + \textit{invisible } h$ should be possible if $\sigma \times BR(Z + \textit{invisible } h) \gtrsim \epsilon\sigma \times BR\Big(Z + Z(\to \nu\bar{\nu})\Big)$, where ϵ is some number in the range of 0.05–0.25. All other backgrounds appear to be well below the signal level.

2.0 RESULTS

We have used the Monte Carlo simulation program Pythia 5.6[8] to make a quantitative study of this situation. The Higgs boson is given a 100% invisible BR. If h has some visible and some invisible decays, the event rates or statistical significance have to be adjusted accordingly. One Z in each process decays to $e^+e^- + \mu^+\mu^-$. The second Z in $q\bar{q} \to ZZ$ decays to $\nu\bar{\nu}$, summed over three families.

Pythia 5.6 gives the production cross section for the Standard Model h. In some theories with an *invisible* h the production cross section will be reduced; for example, in a supersymmetric theory the factor $\sin^2(\beta - \alpha)$ enters. In the favored parameter regions of minimal supersymmetric theories this factor is nearly unity, but in some cases there could be a reduction of signal for which our results would have to be corrected.

For lighter M_h the $\sigma \times BR$ of interest is large enough to give a strong signal. Table 1 gives some event rates, and Figure 1 shows signal/$\sqrt{\text{background}}$, where signal = number of events of $Z(\to ee, \mu\mu) + \textit{invisible } h$ at the SSC assuming integrated luminosity of 10^{40}cm^{-2}, and background = number of events of $Z(\to ee, \mu\mu) + Z(\to \nu\bar{\nu})$ for the same integrated luminosity. This is the appropriate ratio to study because $\sigma(ZZ)$ will be independently normalized. If this becomes an important experiment and the statistical significance is marginal, the SSC can be operated at a greater luminosity, of course. A rapidity region $|\eta| \leq 2.5$ is assumed.

At larger M_h the statistical significance may be large enough to detect an effect at the SSC up to $M_h \lesssim 150$ GeV, covering the needed range. At larger M_h, the P_T distribution of the Z from $q\bar{q} \to Z + h$ is broader than that of the Z from $q\bar{q} \to Z + Z$, so an improvement

in signal/$\sqrt{\text{background}}$ can be obtained by selecting events at larger P_T. This is shown in Figure 1.

Table 1. Number of events at the SSC in the Zh and Wh channels for Higgs mass up to 160 GeV (luminosity $10^{33}\text{cm}^{-2}\text{sec}^{-1}$, for 10^7 secs), with Z ($\rightarrow e^+e^-$ or $\mu^+\mu^-$), W ($\rightarrow e\nu$ or $\mu\nu$), and h decay invisible, in the kinematic region $|\eta| \leq 2.5$. LHC results for the same luminosity are in brackets. Signal/$\sqrt{\text{background}}$ is in the last two columns. Individual run rates for the background processes are used in computing the signal/$\sqrt{\text{background}}$ ratios; therefore, the use of the average value to compute this number will give slightly different results.

Higgs Mass (GeV)	Zh	Wh	$\frac{Zh}{\sqrt{ZZ}}$	$\frac{Wh}{\sqrt{WZ}}$
40	5789 (3074)	47572 (25993)	100.6 (77.4)	369.8 (291.7)
50	3815 (2119)	31692 (17219)	66.9 (53.4)	244.9 (193.0)
60	2850 (1472)	21965 (11627)	49.6 (37.1)	170.0 (130.1)
70	1996 (1053)	15825 (8268)	34.5 (26.2)	122.8 (92.5)
80	1612 (783)	11736 (6009)	28.6 (19.7)	91.0 (67.4)
90	1198 (598)	8903 (4559)	20.5 (14.9)	69.0 (51.3)
100	943 (468)	6882 (3420)	16.6 (11.7)	53.4 (38.3)
110	760 (367)	5371 (2595)	13.2 (9.2)	41.7 (29.2)
120	591 (292)	3912 (1887)	10.2 (7.3)	30.5 (21.3)
130	475 (231)	2700 (1270)	8.2 (5.8)	20.9 (14.3)
140	388 (181)	1606 (747)	6.7 (4.5)	12.4 (8.4)
150	320 (153)	795 (361)	5.5 (3.8)	6.2 (4.0)
160	282 (133)	219 (97)	4.9 (3.3)	1.7 (1.1)

Average Background Rates: ZZ =3326 (1595); WZ =16629 (7944).

In addition, higher-order QCD corrections give stiffer P_T spectra for Higgs boson production[9] opposite gluons, and a similar result here would improve the ability to separate this signal.

Table 1 and Figure 1 show that for most or all of the range of interest a signal is likely to be detectable for a Higgs boson that decays invisibly, but is produced in association with a Z. Similar results are obtained for production in association with a W, which could be used to confirm a possible signal. Although there are more events for the W case, it is, of course, more difficult to reconstruct such events, and further background study would have to be done for the W case.

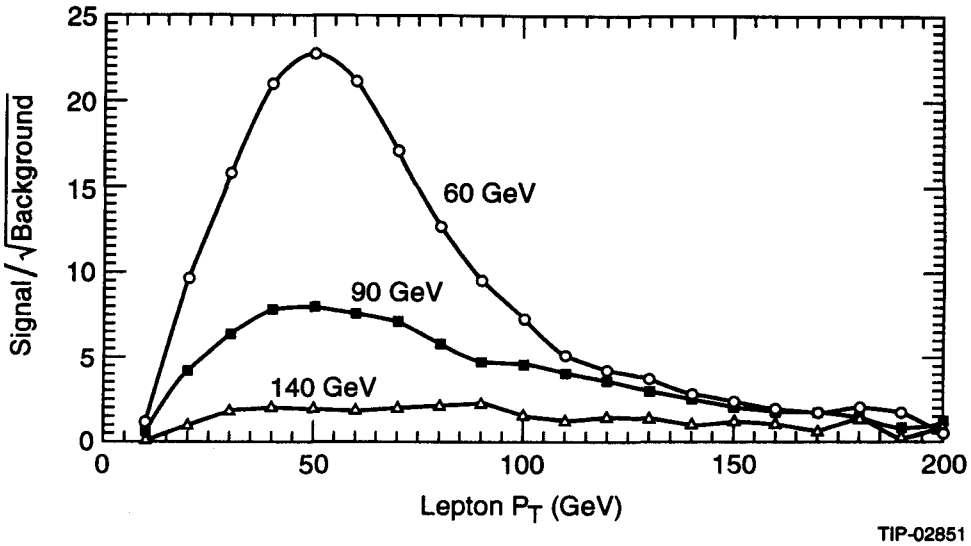

Figure 1. P_T distribution of the Zh signal at the SSC. Lines are labeled by M_h. The curves for Wh are similar. The shape of the curves is determined by the mass of the invisible Higgs boson.

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