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Detecting invisible Higgs bosons at the CERN Large Hadron Collider

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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, $M_h \leq 150$ GeV. If a Higgs boson is detected another way, so that M_h is known, this method may allow a measurement of the branching ratio (B) ($h \rightarrow$ invisible), and may also allow measurement of other branching ratios.

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I. INTRODUCTION

An important aspect of why the European particle-physics community has endorsed the CERN Large Hadron Collider (LHC) as its highest priority is the hope, based on extensive research and several studies, that whatever form nature has chosen for the physics of the Higgs section 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 Ref. [6], H^0,A^0 decays about 20% of the time this way.

We will see below that such invisible Higgs bosons can be discovered at the LHC using the associated production mode $pp \rightarrow Z + h +$ anything, with $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$, and invisible h. It is appropriate to consider production via $q+q \rightarrow Z^* \rightarrow Z+h$, since we assume that the Higgs mechanism is responsible for generating the mass of the gauge bosons; thus the ZZh coupling 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 $h \rightarrow ZZ$ and/or $h \rightarrow WW$ 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 150 GeV (for large M_t), 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. At the CERN 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 $\leq M_h \leq 150$ GeV is the interesting one.

Detection of a normal Higgs boson h decaying into the $b\bar{b}$ mode in associated production with a Z is not considered a favored approach for discovery. That is because of the large QCD background present in the Z plus-2-jet state. For our purposes only leptonic decays of the Z plus missing momentum are used (not including τ decays). The dominant background (irreducible) comes from the electroweak process $q+q \rightarrow Z+Z$, followed by one $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ and the other $Z \rightarrow \nu\nu$. This has a $\sigma \times B$ about the same size as that for our process ($Z+h$ with $Z \rightarrow e^+e^-$ 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 $Z+$invisible h. But because $\sigma(Z+Z)$ will be measured accurately after some time at the hadron colliders, detection of $Z+$invisible h should be pos-

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sible if $\sigma\times B(Z+\text{invisible } h)\geqslant\varepsilon\sigma\times B(Z+Z(\rightarrow\nu\nu))$, where ε is some number in the range 0.05–0.25. Signal/$\sqrt{\text{background}}$ is the appropriate ratio to study because $\sigma(Z+Z)$ will be independently normalized. All other backgrounds appear to be well below the signal level when appropriate cuts are applied as explained in Sec. II below.

II. RESULTS

A program was written to simulate the important properties of a central-tracker-type solenodial detector such as the CMS at the LHC. Z events generated by the Lund programs PYTHIA and JETSET [8] were examined in detail to determine the kinematic cuts necessary to expose the $Z+$ (hidden h) events from all other $Z+$ (significant missing P_T) events. The Lund programs were initialized assuming the Higgs particle is stable with no decay channels and the Z is only allowed to decay leptonically to electrons or muons or to all three families of neutrinos.

If h has some visible and some invisible decays, the event rates or statistical significance have to be adjusted accordingly. 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 sypersymmetric 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.

The principle background that could prevent detecting the $Z+h$ signal events are the $Z+Z$ events where one Z decays leptonically and the other Z decays by neutrinos, thus mimicking a hidden Higgs signal event. This part of the problem was analyzed by our previous work which was published as a Superconducting Super Collider (SSC) note (SSCL-577) in 1992. In the present work, all other $Z+$(missing P_T) events that we are aware of are included in the analysis in order to characterize the detector parameters necessary for isolating signal events from all other possible background events.

The analysis program consists primarily of a series of kinematic cuts which are applied to each event generated by the Lund programs and varied in different runs to optimize the detector parameters required to isolate the signal events. The detector parameters are set and subsequent cuts applied according to an actual isolation scenario. The central tracking region is assumed to cover a pseudorapidity range of ±2.5. Low P_T events may have high rapidities and so we must also assume detectors can resolve energies out to pseudorapidities of ±5.0. Thus the strongest cut to resolve the missing P_T events is the ability of the detector to measure energies at high pseudodrapidities.

The raw events generated were $Z+Z$, $Z+h$, $Z+$gluon and various $Z+$quarks (hard jets) events. The specific quark → hard jet processes which were observed to survive all the cuts were $Z+$(single quark), usually a b quark, or $Z+$gluon, with about a 7 to 3 ratio of these events respectively contributing to the principle interfering background events. The channels generated by the Lund program were $qq\rightarrow Z$, $qq\rightarrow Z+g$, $gq\rightarrow Z+q$, $qq\rightarrow Z+h$, $qq\rightarrow Z+Z$, where q includes light quarks, b, and t.

The first cut in the analysis of each event consisted of rejecting all events which do not satisfy the kinematic constraints of momentum and energy conservation to within 1%. Next, all events are analyzed for their jet production. All the jets in the event are identified and events with any jet P_T exceeding some preselected value in the range 25–45 GeV and in the pseudorapidity range less than ±5.0 are rejected. This range is varied to find the best signal, and this will most likely represent the required forward calorimetry measure-

TABLE I. Number of events at the LHC at center-of-mass energy 14 TeV in the Zh channel per year (10^7 sec) with luminosity 10^{34} $\text{cm}^{-2}\,\text{sec}^{-1}$ for Higgs boson mass up to 150 GeV. The figure of merit, the ratio of signal(S) to squareroot of the total background(B), is in the last column. Detection parameters: pseudorapidity of central-tracker ±2.5; isolation cone angle 0.7 radians; hard cut on P_T of leptons/jets 5.0 GeV; jet P_T cut=45 GeV. Other parameters given in the table.

Higgs boson mass (GeV)	Zh	$S/\sqrt{B}$
60	3386	26
90	1989	15
120	1117	9
150	605	5
Pseudorapidity calorimetry ±4.0; pseudorapidity of missing P_T±4.5; missing P_T cut=65 GeV; P_T cut for the dilepton Z=10 GeV.		
Average background: ZZ=4053, Z jets=13109.		
60	2607	31
90	1608	19
120	953	11
150	552	6.6
Pseudorapidity calorimetry ±4.0; pseudorapidity of missing P_T±4.5; missing P_T cut=75 GeV; P_T cut for the dilepton Z=10 GeV.		
Average background: ZZ=3161, Z jets=3864.		
60	2496	10
90	1577	6.5
120	899	3.7
150	543	2.2
Pseudorapidity calorimetry ±3.5; pseudorapidity of missing P_T±4.0; missing P_T cut=75 GeV; P_T cut for the dilepton Z=10 GeV.		
Average background: ZZ=3086, Z jets=55811.		
60	3855	39
90	1959	20
120	1053	11
150	609	6.2
Missing P_T cut=55 GeV; pseudorapidity of calorimetry and missing P_T±4.7; P_T cut for the dilepton Z=5 GeV.		
Average background: ZZ=4244, Z jets=5301.		
60	2794	41
90	1622	24
120	930	14
150	475	7
Missing P_T cut=65 GeV; pseudorapidity of calorimetry and missing P_T±4.7; P_T cut for the dilepton Z=5 GeV.		
Average background: ZZ=3265, Z jets=1391.		

ment capability of any detector hoping to detect an invisible Higgs boson.

Following the jet P_T cut, possible Z events of interest are tagged by searching for at least one hard isolated lepton with P_T greater than 5 GeV in the central region. Isolated, for this analysis, means the scattering cone represented by an angle of 0.7 radians centered on the lepton or partons which have a P_T greater than 5 GeV. The boost invariant quantity $R=[(\Delta\eta)^2+(\Delta\phi)^2]^{1/2}$ has been used rather than angle. The surviving isolated hard leptons are counted and events are rejected from further analysis which yield no central isolated hard leptons.

If only one isolated hard lepton is found in the central region, then a search is made out to greater pseudorapidities, up to ± 5, for additional isolated hard leptons. Applying this lepton search technique approximately doubled the number of surviving signal events over the number of events surviving with all hard isolated leptons detected only in the central region. We note that in both CMS and ATLAS the central tracker extends to $\eta=2.5$.

After the search for additional leptons out to larger pseudorapidities, events with still only one hard isolated lepton and those events with 3 or more hard isolated leptons are also rejected. This leaves only events with isolated hard dileptons with at least one of the dileptons in the central tracker region.

The dilepton mass was next determined and events with dilepton masses outside the range ± 5 GeV from the Z mass at 91 GeV were rejected.

Events which have survived all the cuts up to this point were then examined for the amount of missing P_T. The missing P_T for each event was derived from the negative vector sum of all detected particles and jets out to a maximum calorimetry pseudorapidity to be determined.

The missing P_T cut was varied from 45 to 75 GeV for difference runs and events were rejected which had missing P_T less than the selected cut. The total number of background events from Z+jets were typically cut by several orders of magnitude in comparison with the $Z+h$ signal events and the principle interfering background event, Z (leptons)+Z (neutrinos). Only the combination of high pseudorapidity resolution and high P_T cuts gives the necessary reduction of the background Z+jets events.

The last cut is performed on the dilepton Z parent, requiring this Z to have a pseudorapidity less than the selected maximum and a P_T of about 10 GeV. This ensures that the Z is indeed recoiling against something invisible.

The surviving event statistics, histograms, cross sections, and LHC counting rates are then calculated and stored for comparison. Many different computer runs were examined for the different cuts selected in order to determine the minimum set of cuts necessary for successfully isolating the $Z+h$ events.

The figure of merit (σ) for detection is defined to be the ratio of the number of signal events to the square-root of the number of background events. Given the kinematic values and ranges of cuts described above and in the accompanying data table, it appears that a figure of merit in excess of about 4 can be achieved for all Higgs boson masses in the range from 60 to 150 GeV. We therefore conclude that an invisible Higgs boson should be detectable at the LHC by applying appropriate kinematic cuts assuming that event calorimetry can be performed out to a pseudorapidity of at least 4.5. The last data runs were made to simulate the detector parameters for the CMS detector at the LHC.

We note that at higher energies to get the same signal resolution with the same luminosity requires even higher rapidity resolution.

Our numerical results together with the parameter choices are displayed in Table I. The results are most crucially dependent on the end cap calorimetry pseudorapidity of the detector, and one must have $\eta>4.0$ to get an adequate signal. The results are much less dependent on other cuts such as, for example, the jet P_T cut.

Recently other works on detecting an invisible Higgs boson have appeared by Choudhury and Roy [9] and Gunion [10]. Gunion considers associated production of $h\,t\bar{t}$ and concludes that an invisible Higgs of mass up to 250 GeV could be detected at the LHC. Choudhury and Roy consider associated production of Zh and Wh at the LHC and reach similar conclusions to ours, but without a PYTHIA-type simulation. We thank Torbjorn Sjostrand for helpful discussions on PYTHIA and the Lund model.

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