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Investigation of invisible decays of the Higgs boson at a future e^+e^- linear collider

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Abstract

Several models beyond the Standard Model predict invisible decay products of a Higgs boson. The sensitivity of a future e^+e^- linear collider for discovering this final state and measuring the branching ratio of a Higgs boson decaying into an invisible final state is investigated. The study has been performed assuming a data set corresponding to 500 fb^{-1} collected at a center-of-mass-energy of 350 GeV. The Higgs-Strahlung-process $e^+e^- \to$ZH with subsequent decay of the Z boson into a quark final state has been analysed. The Higgs boson is expected to be discovered down to branching ratios of approximately 2% for masses between 120 and 160 GeV assuming the production cross section as in the Standard Model. The expected accuracy on the measurement of the branching ratio into invisible final states as a function of this branching ratio is also presented.

1 Introduction

A plentitude of extensions beyond the Standard Model introduce new particles, which remain undetectable in the detectors, but with a direct coupling to Higgs bosons in this models. Such models include Majorons (J) [2], Neutralinos (χ) in sypersymmetrci theories [1], mixing of the ordinary Higgs bosons with Graviscalars in certain models of large extra dimensions [3] and the so-called stealthy Higgs scneario [4]. The experimental signature are invisible decays of the Higgs boson. Preliminary LEP results exclude Higgs masses below 114.4 GeV assuming a production cross section given by the Standard Model and 100% branching ratio in invisible final states [5].

This study evaluates the potential of a future e^+e^- linear accelerator for the discovery of invisible decays of a Higgs boson and the measurement of the branching ratio to the invisible final state. The process considered is the Higgs-Strahlung-process with subsequent decays of the Z boson into a pair of quarks. The Higgs boson mass range of 120 GeV to 160 GeV is investigated. It is assumed that the width of Higgs boson is negligible compared to the missing mass resolution of the detector and that the structure of the coupling of the Higgs boson to the Z boson is the same as predicted by the Standard Model. The study has been performed assuming a data set corresponding to 500 fb^{-1} collected at a center-of-mass-energy of 350 GeV.

2 Monte Carlo samples and detector simulation

The signal process $ZH \to q\bar{q}\ inv.$ has been generated firstly with HZHA [9] with includes the invisible decay mode, but does not include the effect of beamstrahlung and secondly with PYTHIA [10] where $H \to \mu\mu$ decays have been generated and afterwards before the detector simulation is applied the muons have been disregarded from the list of generated particles. PYTHIA is interfaced to CIRCE [11] to include effects of beamstrahlung. All background processes considered, i.e. $Z/\gamma \to q\bar{q}$ and pair production of W and Z bosons, have been generated with PYTHIA. The effect of initial state radiation is taken into account in all event generators used. The response of a a future e^+e^- linear collider detector is simulated with SIMDET [12] version 3.0 using the default settings.

The following cross section obtained with PYTHIA have been used in the evaluation of selection and the measurement of the branching ratio of Higgs to invisible particles: $\sigma_{ZH} = 157.3$ (130.3, 106.8) fb for a Higgs boson mass of 120 (140, 160) GeV, $\sigma_{Z/\gamma\to q\bar{q}} = 40650$ fb, $\sigma_{WW} = 13270$ fb and $\sigma_{ZZ} = 1009$ fb.

3 Selection

The signal topology is characterised by two hadronic jets and large missing energy and transverse momentum. The invariant mass of the two jets should be consistent with the mass of the Z boson and the missing mass calculated as the recoil to the hadronic system should be consistent with the mass of the Higgs boson under consideration. The dominant backgrounds are $Z/\gamma \to q\bar{q}$, WW and ZZ production. The backgrounds are suppressed by means of simple basic cuts, while retaining a good efficiency for signal events. The selection is by far not optimised and leaves certainly some room for improvements in the future.

The following cuts have been applied:

(0) The event has to be classified as a hadronic final state: at least 10 reconstructed energy objects and at least 7 reconstructed tracks are required.

(1) The event is forced into two jets using the Durham jet finding scheme. The energy of both jets has to exceed 10 GeV and each jet has to contain at least 3 tracks in order to reject jets from final state photon radiation or leptonic jets.

(2) The visible energy of the event should be in the range between $0.3\times\sqrt{s}$ and $0.7\times\sqrt{s}$.

(3) The total tranverse momentum should be larger than 70 GeV.

(4) The direction of the missing momentum or equivalently of the dijet system should point to central parts of the detector $|\cos\theta_{jj}|$ <0.7.

(5) The total number of reconstructed energy flow objects should be at least 25.

(6) The visible mass should be consistent with the Z-boson hypothesis: $|M_{vis.} - M_Z|$ <7.5 GeV.

(7) The missing mass should be consistent with the mass of the Higgs boson under consideration: $|M_{mis.} - M_H| <15.$ GeV.

The distributions for the variables used in the cut based selection are shown in figures 1 and 2.

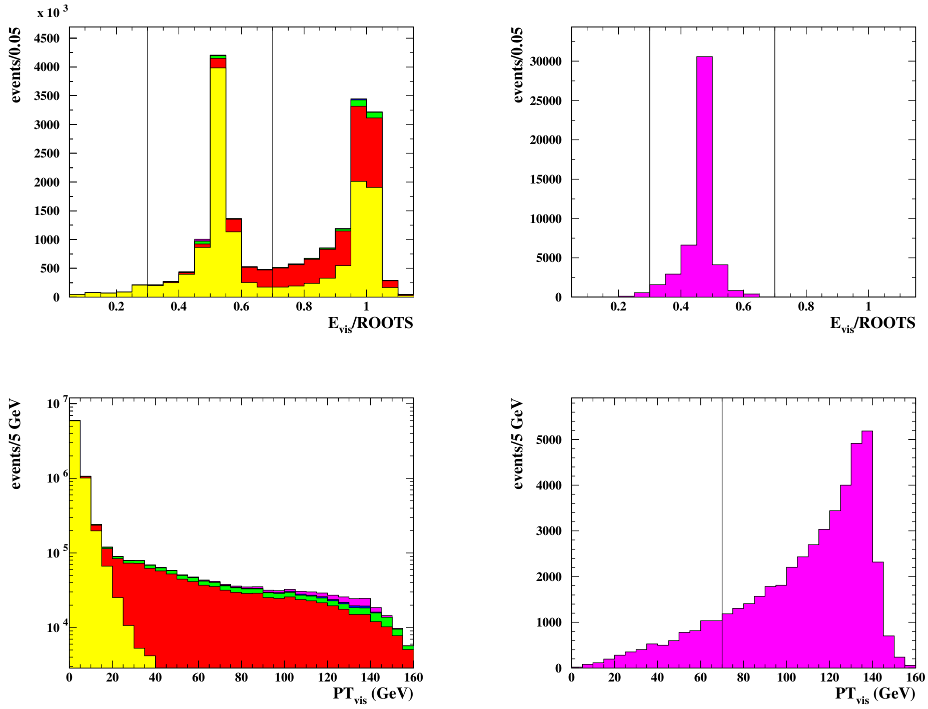

Figure 1: *Distribution of variables used in the selection. Upper line* $E_{Vis}/\sqrt{s}$ *and lower line* P^t_{vis} *for background in left and signal in right column. The vertical lines indicate the position of the cuts. The HZ signal is shown in magenta,* $Z/\gamma \to q\bar{q}$ *background in background yellow, WW background in red and ZZ background in green.*

The number of background events and signal efficiencies after each of the seven consecutive cuts is shown in table 1. The last line is only valid for the a Higgs boson mass of 120 GeV. The performance of the selection for all three masses under consideration after the final cut is shown in table 2. The lower one of the two efficiencies is used in the following. The column denoted $\mathrm{ZH}_{\mathrm{BG}}$ gives the number of background events from ZH production with the

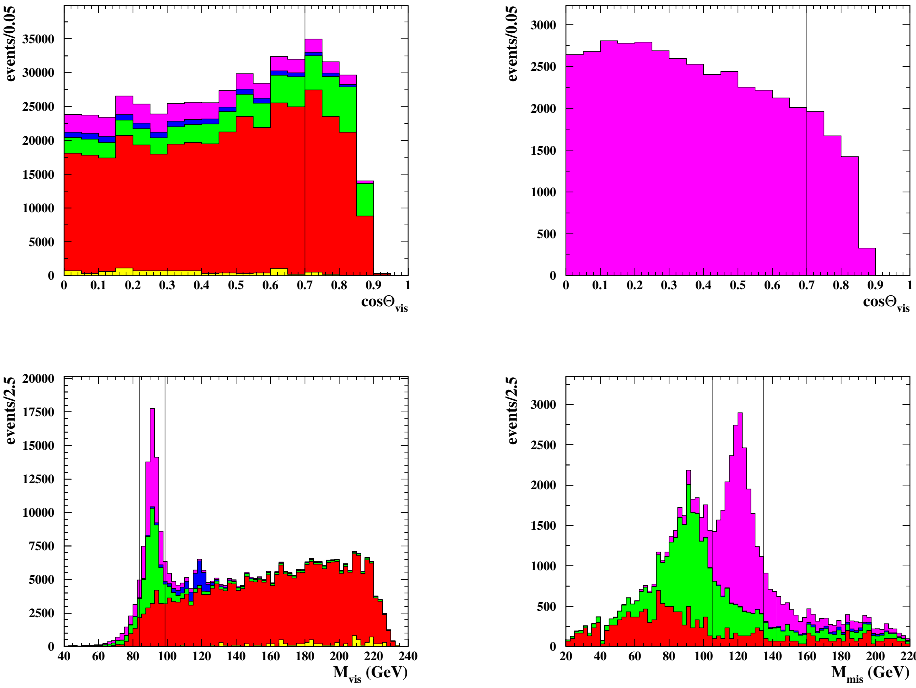

Figure 2: *Distribution of variables used in the selection. Upper line* $\cos\theta_{vis}$ *for background in left and signal in right column. Lower line* M_{vis} *(left) and* M_{mis} *(right) for background and signal. The vertical lines indicate the position of the cuts. The HZ signal is shown in magenta,* $Z/\gamma \to q\bar{q}$ *background in background yellow, WW background in red and ZZ background in green.*

Higgs boson decaying into SM particles. The numbers in this column assume a vanishing branching ratio for the decay of the Higgs boson in invisible final states. The efficiencies obtained from the MC event generators differ by 1.5% at most. The smaller ones are used in evaluation of the results leading to conservative estimates.

4 Results

The expected uncertainty on the determination of the branching ratio of Higgs to invisible particle decays can be calculated using the number of ex-

Cut	$Z\gamma$	WW	ZZ	ZH_{BG}	Eff.(HZHA)	Eff.(Pythia)
(0)	1.3×10^7	5937790	452238	70193	99.0%	95.5 %
(1)	7.2×10^6	1061370	139779	16506	96.7%	94.2 %
(2)	8943	359418	632118	12192	82.3%	80.6 %
(3)	8231	278869	40675	10766	71.6%	69.8%
(5)	8231	271007	39089	10688	69.3%	67.7%
(6)	0	188877	24134	775	50.6%	48.3%
(7)	0	1824	4732	85	34.0%	33.0%

Table 1: *Number of remaining background events and signal efficiency after each of the seven cuts for a Higgs boson mass of 120 GeV. The column denoted* ZH_{BG} *gives the number of expected background events from ZH production with H decaying to SM final states assuming a vanishing branching ratio to invisible decay modes.*

$M_H(GeV)$	ZZ	WW	ZH_{BG}	Eff.(HZHA)	Eff.(Pythia)
120	4732	1824	85	34.0%	33.0 %
140	2145	1360	72	37.7%	36.2 %
160	1360	1028	58	40.5%	39.9 %

Table 2: *Number of remaining background events, signal efficiency after the final cut for the three investigated Higgs boson masses of 120, 140 and 160 GeV. The column denoted* ZH_{BG} *gives the number of expected background events from ZH production with H decaying to SM final states assuming a vanishing branching ratio to invisible decay modes.*

pected signal events N_{sig}, the number of expected background events N_{BG}, which both depend on the assumed branching ratio BR of a Higgs boson decaying into invisible particles, and the expected uncertainty on the measurement of the production cross section for Higgs-Strahlung σ_{ZH} [6,7] (see table 3). The number of expected background events is given by:

$$N_{BG} = N_{WW} + N_{ZZ} + (1. - BR) \cdot N_{HZ}^{BG} \tag{1}$$

and the number of expected signal events by

$$N_{Sig} = \epsilon \cdot BR \cdot \sigma_{ZH} \cdot \mathcal{L}, \tag{2}$$

$M_H (GeV)$	σ_{ZH}	$\Delta\sigma_{ZH}/\sigma_{ZH}$
120	157.27 fb	0.025
140	130.27 fb	0.027
160	106.82 fb	0.030

Table 3: *Expected accuracy on the measurement of the Higgs-Strahlung cross section (from [6, 7]).*

where $\mathcal{L}$ denotes the luminosity and ϵ the signal selection efficiency. The relative uncertainty on the branching ratio is then given by:

$$\frac{\Delta BR}{BR} = \sqrt{\left(\frac{\sqrt{N_{BG} + N_{Sig}}}{N_{Sig}}\right)^2 + \left(\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}}\right)^2} \tag{3}$$

The expected relative accuracy on the direct determination of the branching ratio of Higgs to invisible particle decays is shown in figure 3 and left side of figure 4 for small assumed branching ratios.

The results are also compared to the ones obtained by an indirect method using the model independent measurement of the Higg-Strahlungs cross section and the measurements of the branching ratios of the visible decay modes of the Higgs boson [7, 8]. For invisible branching ratios below $\approx 55\%$ the direct measurement is more precise than the indirect determination. For large branching ratios the direct method is limited by the uncertainty on the Higgs-Strahlung- cross section. The relative accuracy is better than 3% (10%) assuming a branching ratio into invisible final states of larger than 20% (5%). The signal significance, defined as $N_{Sig}/\sqrt{N_{BG}}$, is shown in figure 5. Invisible decay modes of a Higgs boson can be discovered with a significance of at least five standard deviations down to branching ratios of 2.5% (1.5%) for a Higgs boson mass of 120 GeV (140 and 160 GeV). The extension of the mass range, the inclusion of leptonic decays of the Z boson and the interpretation of the results in various models predicting invisible decays of a Higgs boson is content of further studies and will be described in another forthcoming note.

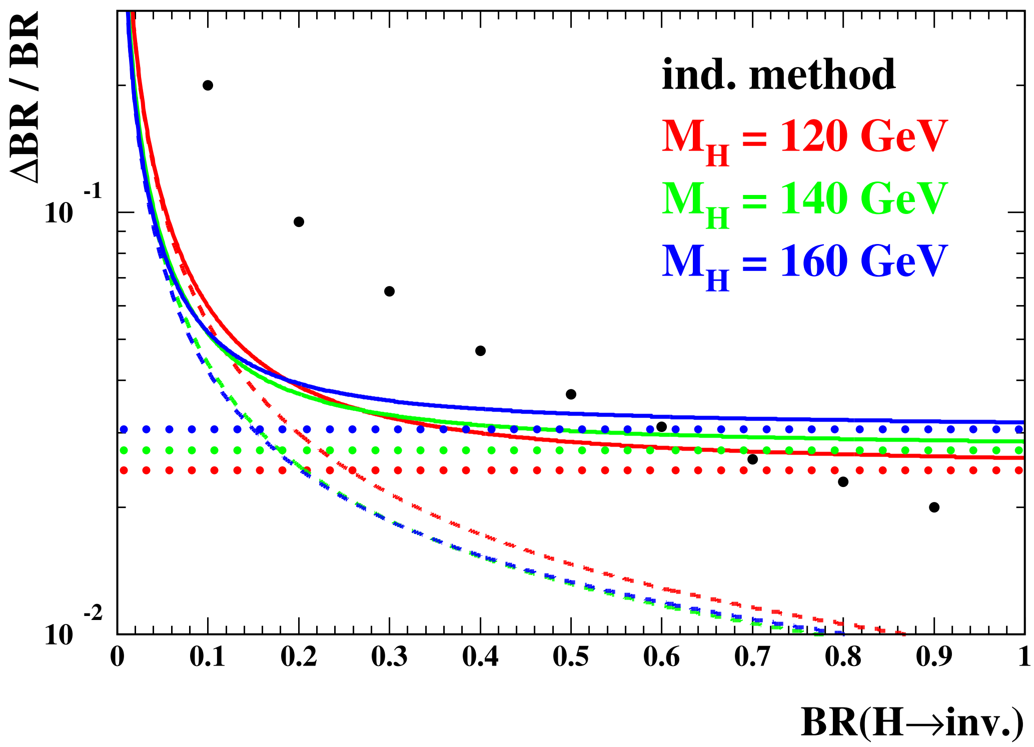

Figure 3: *Relative accuracy of the measurement of the branching ratio H into invisible final states as function of the branching ratio Higgs to invisible. The red (green, blue) lines show the results for a Higgs boson of mass 120 (140, 160) GeV for a data set corresponding to 500 fb^{-1} collected at a center-of-mass energy of 350 GeV. The solid lines give the total expected uncertainty, the dashed lines show the contribution from the selection of invisible Higgs decays and the dotted lines the contribution from the decay mode independent cross section measurement. For comparison the result of the indirect method is also shown as black dots (see text for details).*

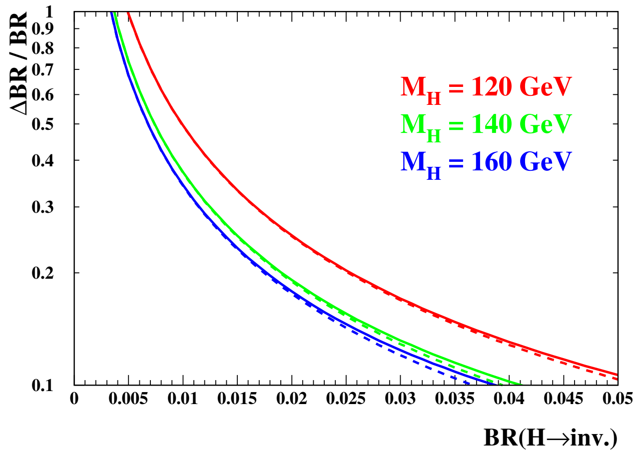

Figure 4: *Relative accuracy of the measurement of the branching ratio H into invisible final for a branching ratio Higgs to invisible less than 5%. The line style is the same and colour code is the same in figure 3.*

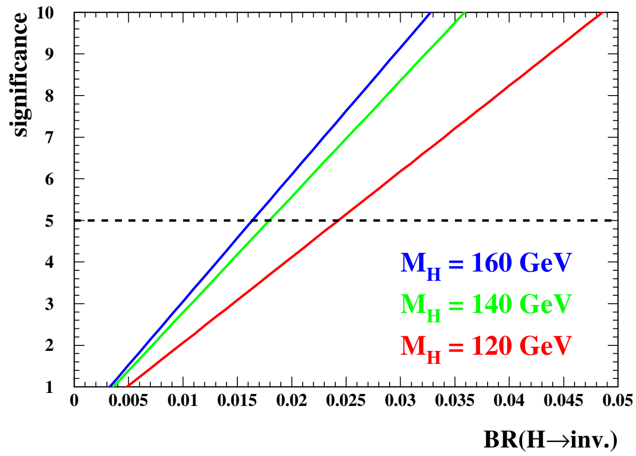

Figure 5: *Expected significance for the observation of the signal process as a function of the branching ratio Higgs to invisible. The colour code is the same as in figure 3.*

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