

## Experimental Aspects of Higgs Physics at the ILC\*

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### Abstract

Recent progress in Higgs boson studies for the International  $e^+e^-$  Linear Collider (ILC) is reported. These studies include extended simulations of the measurement of the Higgs mass, measurements of the Higgs boson branching ratios at higher center-of-mass energies, and methods for extracting the Higgs boson self-coupling. Also, the interplay between the LHC and the ILC in the measurement of the top Yukawa coupling and in the extraction of the supersymmetric Higgs sector parameters is discussed.

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# 1 Introduction

With an  $e^+e^-$  center of mass energy in the range of 90 to 1000 GeV, a well defined initial state, and a clean experimental environment, the International  $e^+e^-$  Linear Collider (ILC) will be an ideal accelerator at which to study the properties of Higgs bosons. An extensive literature [1–5] exists detailing how the ILC can measure the masses, widths, couplings, and quantum numbers of Higgs bosons in a model independent manner with high precision. In this paper recent progress on experimental aspects of ILC Higgs boson physics will be presented. The discussion includes beam-related systematic errors in Higgs mass measurements, hadronic Higgs decays, Higgs boson phenomenology at  $\sqrt{s} = 1000$  GeV, and LHC/ILC synergy.

## 2 Beam Related Systematic Errors in the Higgs Mass Measurement

The Higgs mass will be measured in the process  $e^+e^- \rightarrow Zh$  using the recoil mass technique and the direct multi-jet technique if the fully hadronic decay branching ratio is high enough. In the recoil mass technique the mass of the system opposite a  $Z$  boson decaying to  $e^+e^-$  or  $\mu^+\mu^-$  is measured without regard to the Higgs decay. In the direct multi-jet technique, jets from the Higgs decay are combined with the jets or leptons from the  $Z$  boson decay in a kinematical fit, and the mass is extracted from the fitted four-vectors.

In both techniques a kinematical constraint utilizing the beam energy is employed. Systematic errors in the measurement of the beam energy scale and the differential luminosity distribution therefore contribute to the total Higgs mass error.

### 2.1 Differential luminosity measurement

The effects of beamstrahlung are described by a double differential luminosity distribution  $d^2L/dx_1dx_2$ , where  $x_1$  and  $x_2$  are the energy fractions of the electrons and positrons. Most analyses utilize the acollinearity distribution of Bhabha events to reconstruct this distribution. Studies indicate that under idealized conditions where the function  $d^2L/dx_1dx_2$  factorizes into two identical one-dimensional distributions of the form  $f(x_i) = a_0\delta(1 - x_i) + a_1x_i^{a_2}(1 - x_i)^{a_3}$ , the differential luminosity can be measured to an accuracy of 1%, assuming  $3 \text{ fb}^{-1}$  at  $\sqrt{s} = 500$  GeV [6].

In a study of beam related systematic errors on Higgs mass measurements, Raspereza has shown that a 10% measurement error of the differential luminosity parameters  $a_i$  leads to a 10 MeV error on the Higgs mass when the direct multi-jet technique is used [7].

### 2.2 Beam energy scale

The beam energy scale can be measured to an accuracy of about 200 ppm by combining data from beam energy spectrometers upstream and downstream of the interaction point

with beam energy estimates from physics processes such as  $e^+e^- \rightarrow \gamma Z$ ,  $ZZ$ ,  $e^+e^-$  and  $\mu^+\mu^-$  [8].

The dependence of the Higgs mass error on the beam energy scale error has been studied by several groups. Raspereza studied the direct multi-jet technique assuming a 120 GeV Standard Model Higgs boson and found  $\delta M_H/\delta E_{\text{cm}} = 0.5$  for the  $bbll$  final state and  $\delta M_H/\delta E_{\text{cm}} = 0.4$  for the  $bbqq$  final state. Due to the fact that no Higgs decay information is utilized, the recoil mass technique has a much stronger dependence on the beam energy measurement with  $\delta M_H/\delta E_{\text{cm}} = 2.9$ .

The statistical error and energy scale systematic error for a 120 GeV standard model Higgs boson are summarized in Table 1.

technique	statistical error (GeV)	energy scale systematic error (GeV)
recoil mass	0.117	0.200
$ZH \rightarrow l^+l^-b\bar{b}$	0.072	0.035
$ZH \rightarrow q\bar{q}b\bar{b}$	0.046	0.028
combined	0.037	0.027

Table 1: *Statistical and energy scale systematic errors for the Higgs mass measurement at the ILC assuming a standard model Higgs with  $M_H = 120$  GeV,  $\sqrt{s} = 350$  GeV,  $500 \text{ fb}^{-1}$  luminosity, and a 200 ppm center-of-mass energy scale error. The combined energy scale systematic error includes the effects of correlations between the three measurements.*

### 3 Hadronic Branching Ratio Measurement

For some time European and American working groups have come to different conclusions about how well hadronic Higgs branching ratios can be measured [2,3]. This is illustrated in the last two columns of Table 2, where the branching ratio error estimates from the TESLA TDR are displayed alongside those reported at Snowmass 2001. Recently, a new analysis presented by Thorsten Kuhl at LCWS 2004 [9] splits the difference, as shown in the first column of Table 2 .

selection	LCWS	TESLA TDR	Snowmass
	2004	(2001)	2001
$\Delta(\sigma \times BR(H \rightarrow b\bar{b})) / (\sigma \times BR(bb))_{SM}$	1.0%	0.9%	1.6%
$\Delta(\sigma \times BR(H \rightarrow c\bar{c})) / (\sigma \times BR(cc))_{SM}$	12.0%	8.0%	19.0%
$\Delta(\sigma \times BR(H \rightarrow gg)) / (\sigma \times BR(gg))_{SM}$	8.2%	5.1%	10.4%

Table 2: *Comparison of the relative errors obtained with Kuhl's new analysis and previous analyses from the TESLA TDR and the Snowmass 2001 workshop.*

Compared to the 2001 TESLA TDR results, the new analysis by Kuhl uses an improved version of the TESLA detector fast Monte Carlo program SIMDET [10]. Results on tracking efficiency and impact parameter resolution from studies using the full TESLA detector

Monte Carlo and emulated pattern recognition have been included in the new version of SIMDET. These newly incorporated effects tend to worsen the charm tagging capabilities of the detector. On the other hand the LCWS 2004 errors are better than those reported at Snowmass 2001 due to the superiority of maximum likelihood analyses of neural net variables over cuts-based analyses.

## 4 Studies at $\sqrt{s} = 1000$ GeV

### 4.1 Higgs self-coupling

The Higgs potential  $V(\eta_H)$  is probed through measurements of the triple and quartic Higgs self-couplings  $\lambda$  and  $\tilde{\lambda}$  :

$$V(\eta_H) = \frac{1}{2}M_H^2\eta_H^2 + \lambda v\eta_H^3 + \frac{1}{4}\tilde{\lambda}\eta_H^4 \quad ,$$

where  $\eta_H$  is the Higgs boson field and  $v$  is the Higgs vacuum expectation value. In the Standard Model  $\lambda = \tilde{\lambda} = M_H^2/(2v^2)$ , so that a comparison of the measured values of  $\lambda$ ,  $\tilde{\lambda}$  and  $M_H$  will constitute an important test of electroweak symmetry breaking models.

The triple Higgs self-coupling  $\lambda$  will be measured at the ILC at  $\sqrt{s} = 500$  GeV in the Higgstrahlung process  $e^+e^- \rightarrow ZH^* \rightarrow ZHH$ . Assuming  $500 \text{ fb}^{-1}$  luminosity, studies have shown that an accuracy of  $\delta\lambda/\lambda = 0.28$  can be achieved for a Higgs mass of 120 GeV [11].

Recently, the possibility of measuring the triple Higgs coupling at the ILC at  $\sqrt{s} = 1000$  GeV using the WW fusion process  $e^+e^- \rightarrow \nu_e\bar{\nu}_e W^*W^* \rightarrow \nu_e\bar{\nu}_e H^* \rightarrow \nu_e\bar{\nu}_e HH$  has been considered [12]. Assuming  $1000 \text{ fb}^{-1}$  luminosity and 80% left-handed electron polarization, a study of  $e^+e^- \rightarrow \nu_e\bar{\nu}_e HH \rightarrow \nu_e\bar{\nu}_e b\bar{b}b\bar{b}$  found that a triple Higgs coupling accuracy of  $\delta\lambda/\lambda \approx 0.12$  could be achieved [13]. Further improvement is expected by extending the analysis to decay topologies other than  $HH \rightarrow b\bar{b}b\bar{b}$ .

### 4.2 Higgs branching ratios

CLIC studies have demonstrated that Higgs production through the WW fusion process  $e^+e^- \rightarrow \nu_e\bar{\nu}_e H$  at  $\sqrt{s} = 3000$  GeV can be used to probe rare Higgs decays [14,15]. A recent study has shown that such decays can also be probed through WW fusion at the ILC at  $\sqrt{s} = 1000$  GeV [16].

Consider, for example, the  $b\bar{b}$  decay of a 200 GeV Higgs boson, which is inaccessible at  $\sqrt{s} = 350$  GeV, and the  $\gamma\gamma$  decay of a 120 GeV Higgs boson, whose branching fraction can be measured with a relative accuracy of 25% at  $\sqrt{s} = 350$  GeV with  $500 \text{ fb}^{-1}$  luminosity [17]. The visible mass distributions for these two scenarios are displayed in Figure 1 assuming  $\sqrt{s} = 1000$  GeV,  $1000 \text{ fb}^{-1}$  luminosity, -80% initial electron polarization and +50% initial positron polarization. A measurement of the cross-section times branching ratio leads to relative branching ratio errors of 9% for the  $b\bar{b}$  decay of a 200 GeV Higgs boson and 5% for the  $\gamma\gamma$  decay of a 120 GeV Higgs boson.

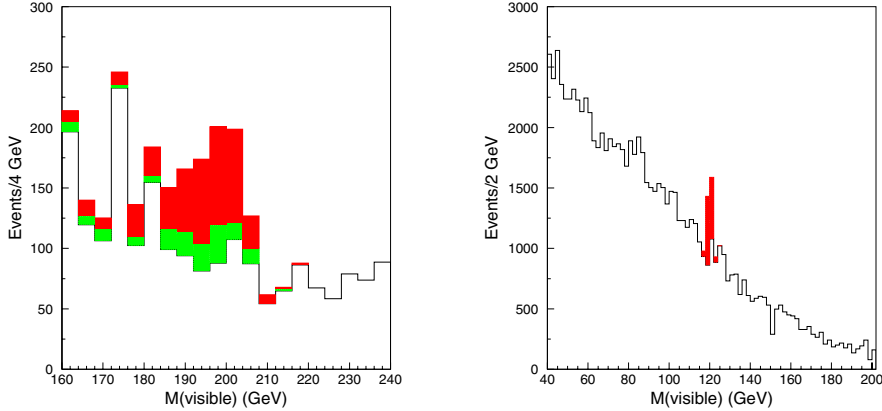


Figure 1: Histograms of the visible mass following  $e^+e^- \rightarrow \nu_e\bar{\nu}_e H$  selection cuts at  $\sqrt{s} = 1000$  GeV for the  $b\bar{b}$  decay mode and  $M_H = 200$  GeV (left) and for the  $\gamma\gamma$  decay mode and  $M_H = 120$  GeV (right). The histograms contain non-Higgs SM background (white), signal Higgs decay (red) and non-signal Higgs decays (green).

## 5 LHC/ILC Complementarity

### 5.1 Top Yukawa coupling

The top Yukawa coupling  $g_{t\bar{t}H}$  will be probed at the LHC by measuring the cross-section for  $gg \rightarrow t\bar{t}H \rightarrow t\bar{t}b\bar{b}$ ,  $t\bar{t}W^+W^-$ . When ILC Higgs branching ratio measurements are combined with LHC cross-section measurements, the top Yukawa coupling can be measured with a relative accuracy of  $\Delta g_{t\bar{t}H}/g_{t\bar{t}H} = 0.13 - 0.17$  for Higgs boson masses between 120 and 200 GeV [18].

At  $\sqrt{s} = 800$  GeV the top Yukawa coupling can be probed directly at the ILC using  $e^+e^- \rightarrow t\bar{t}H$ . A relative accuracy of  $\Delta g_{t\bar{t}H}/g_{t\bar{t}H} = 0.06 - 0.13$  can be achieved for Higgs boson masses between 120 and 200 GeV assuming  $\sqrt{s} = 800$  GeV and  $1000 \text{ fb}^{-1}$  luminosity [19].

### 5.2 Consistency test of the SUSY Higgs system and $A_t$ measurement

A recent study provides examples of how precision Higgs boson measurements at the ILC can be combined with LHC measurements of the masses of SUSY particles to test supersymmetric relationships and extract electroweak scale SUSY parameters [20]. In one example, LHC measurements of the masses of the pseudoscalar Higgs  $A$ , the bottom squarks  $\tilde{b}_1$ ,  $\tilde{b}_2$ , and top squarks  $\tilde{t}_1$ ,  $\tilde{t}_2$  are combined with ILC measurements of the masses of the top quark and lightest Higgs boson to predict the branching ratios of the lightest Higgs boson to  $b\bar{b}$  and  $WW^*$ . The dark blue splotches in Figure 2(a) indicate the allowed regions for the Higgs branching ratios to  $b\bar{b}$  and  $WW^*$ , while the bands for the ILC's Higgs branching

ratio measurements show how well these predictions will be tested. If the ILC branching ratio measurements are consistent with the MSSM predictions then the branching ratio measurements also provide an indirect measurement of the trilinear coupling  $A_t$ .

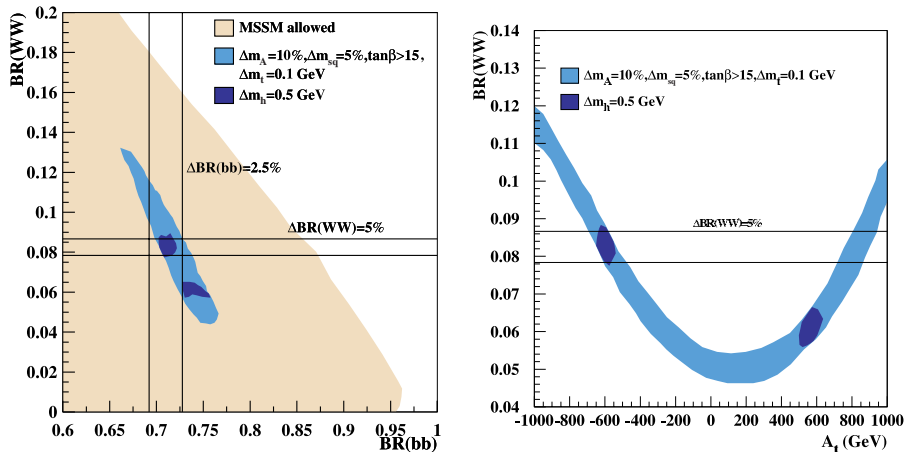


Figure 2: Theoretical predictions for the allowed values of the branching ratios of the lightest MSSM Higgs boson to  $WW^*$  and  $b\bar{b}$  under different experimental assumptions (left), and predictions for the allowed values of the branching ratio of the lightest MSSM Higgs boson to  $WW^*$  and the trilinear coupling  $A_t$  (right). Also shown is the expected branching ratio precision from ILC measurements.

## 6 Conclusion

Table 3 summarizes the accuracy with which Higgs branching ratios, the total Higgs decay width, the top Yukawa coupling and the Higgs self-coupling  $\lambda$  can be measured at the ILC through a combination of  $500 \text{ fb}^{-1}$  luminosity at  $\sqrt{s} = 350$  GeV and  $1000 \text{ fb}^{-1}$  luminosity at  $\sqrt{s} = 1000$  GeV [13, 16, 19, 21, 22].

In summary, there has been progress in understanding beam related systematic errors in the measurement of Higgs boson masses at the ILC. It has also been shown that Higgs physics research at  $\sqrt{s} = 1000$  GeV produces improvements in Higgs branching ratio and self-coupling measurements, even if the Higgs boson mass is less than 200 GeV. Finally, it is not hard to find examples of LHC/ILC complementarity in studies of Higgs and SUSY physics. The ILC's few hundred MeV Higgs mass measurement and few percent branching ratio measurements are used repeatedly in these studies.

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	Higgs Mass (GeV)			
	120	140	160	200
$\Delta B_{bb}/B_{bb}$	0.016	0.018	0.020	0.090
$\Delta B_{WW}/B_{WW}$	0.020	0.018	0.010	0.025
$\Delta B_{gg}/B_{gg}$	0.023	0.035	0.146	
$\Delta B_{\gamma\gamma}/B_{\gamma\gamma}$	0.054	0.062	0.237	
$\Delta B_{\tau\tau}/B_{\tau\tau}$	0.050	0.080		
$\Delta B_{cc}/B_{cc}$	0.083	0.190		
$\Delta\Gamma_{tot}/\Gamma_{tot}$	0.034	0.036	0.020	0.050
$\Delta g_{tH}/g_{tH}$	0.060	0.090	0.080	0.130
$\Delta\lambda/\lambda$	0.120			

Table 3: *Relative accuracies for the measurement of Higgs branching ratios, the Higgs boson total decay width, the top Yukawa coupling  $g_{tH}$  and the triple Higgs coupling  $\lambda$  obtained through a combination of  $500 \text{ fb}^{-1}$  luminosity at  $\sqrt{s} = 350 \text{ GeV}$  and  $1000 \text{ fb}^{-1}$  luminosity at  $\sqrt{s} = 1000 \text{ GeV}$ .*

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