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Measurement of the Higgs Boson Coupling to the Top Quark and the Higgs Boson Self-coupling at the ILC

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Abstract

The International Linear Collider is a proposed 50 km electron-positron collider in the Kitakami hills in northern Japan. Precision measurements of Higgs properties and direct searches for new physics will complement the LHC experiments and their upgrades in our drive to answer open questions about the universe and the origin of matter. Two detector concepts have been validated as being feasible to deliver the necessary precision. In its baseline configuration the machine has a collision energy of about 500 GeV, upgradeable to 1 TeV. The electron beam is 80% polarized. The polarization of the positron beam is 30% at 500 GeV and 20% at 1 TeV. The integrated luminosity in a high-luminosity scenario is 1.6 ab^{-1} at 500 GeV and 2.5 ab^{-1} at 1 TeV. The measurements of the Higgs boson self-coupling and the coupling to the top quark are important pieces of the ILC physics program.

Keywords: Higgs boson, top quark, ILC

1. Introduction

The discovery of the Higgs boson by the LHC experiments ATLAS and CMS completes the particle content of the Standard Model (SM) of particle physics. However, the Standard Model does not accomodate answers to some fundamental questions about the universe. The nature of dark matter and dark energy, or the size of the baryon asymmetry of the universe, which results in our very existence, cannot be explained within the current framework. In the absence of direct observation of new phenomena at the LHC, precision measurements of the properties of the Higgs boson offer a compelling way to find pathways to theories beyond the Standard Model that can explain these questions and more.

In the SM, the strength of the Yukawa interaction y_f between the Higgs boson and a fermion of mass m_f is given by $y_f = \sqrt{2} m_f v$, with the vacuum expectation value $v \approx 246$ GeV. The Yukawa coupling to the top quark, the heaviest known fundamental particle, is expected to be large, with a strength of ≈ 1 in the SM. In spite of this, the measurement of the top quark Yukawa coupling in direct observation of the $\mathrm{t\bar{t}H}$ final state is challenging at the LHC due to the complex final states and large QCD background.

The Higgs potential after electroweak symmetry breaking can be written as Equation 1. The tri-linear Higgs self-coupling λ_{HHH} in the SM is fully determined by the Higgs mass, $m_H^2/2v^2 \equiv \lambda \equiv \lambda_{\mathrm{HHH}} \equiv \lambda_{\mathrm{HHHH}}$. Similarly to the measurement of the top quark Yukawa coupling, the measurement of the tri-linear Higgs self-coupling at the LHC is complicated by complex final states and a large QCD background.

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \sigma)^2 - \lambda v^2 \sigma^2 - \lambda_{\mathrm{HHH}} v \sigma^3 - \frac{1}{4}\lambda_{\mathrm{HHHH}} \sigma^4 \qquad (1)$$

The International Linear Collider is a proposed $\mathrm{e^+e^-}$ collider with a maximum CM energy of $\sqrt{s} = 1$ TeV. It has a broad physics potential that is complementary to

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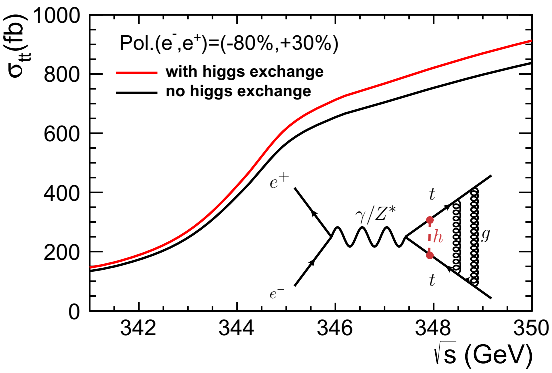

Figure 1: The cross section of top quark pair production above threshold is sensitive to the top quark Yukawa coupling. A measurement of the production cross section at a 500 GeV ILC could achieve a precision of 5.9%

the LHC, and precision measurements of Higgs boson couplings are an integral part of the physics program. While both, the measurements of the top quark Yukawa coupling and the tri-linear Higgs self-coupling remain challenging, the high resolution of the proposed detector concepts allows to disentangle the high-multiplicity signal from the background to enable measurements at the few percent level, and the few sigma level, respectively.

2. Measurement of the top quark Yukawa coupling

At the ILC a first measurement of the top Yukawa coupling can be obtained from the cross section of $e^+e^- \to t\bar{t}$ above threshold, see Figure 1. The achievable precision on the top quark Yukawa coupling in a 3-parameter fit at 500 GeV ILC with an integrated luminosity of 500 ab^{-1} is 5.9% [1].

A measurement in direct observation is less sensitive to theoretical uncertainties in the higher order corrections to the top pair cross section. Figure 2 shows the Feynman diagram of the 8-jet final state of the $t\bar{t}H$ process. A dedicated analysis of this channel, as well as a 6-jet final state in both ILC detector concepts achieves a precision of 4.5% or better with 1 ab^{-1} at a 1 TeV ILC [2]. The analyses are summarized in Table 1. The full ILC program is estimated to achieve a precision of ≈ 2% on the top quark Yukawa coupling, shown in Table 2. Figure 3 (left) shows the cross sections of the signal process with and without higher order QCD corrections, as well as the dominant background processes to the measurement of the $t\bar{t}H$ final state at energies covered by the ILC program laid out in the TDR.

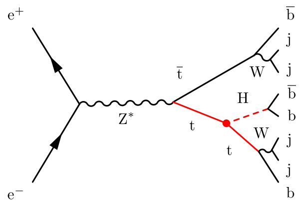

Figure 2: Feynman diagram of the process $e^+e^- \to t\bar{t}H$ with subsequent hadronic decays to four b-jets and four light quark jets.

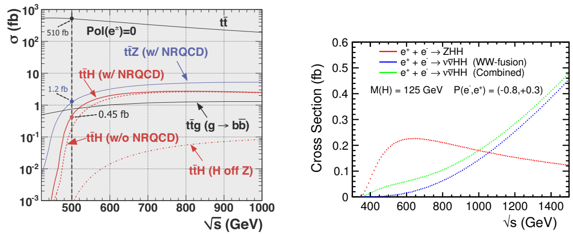

Figure 3: (Left) Production cross section of various processes resulting in a $t\bar{t}b\bar{b}$ final state. (Right) Cross section versus collision energy of the dominant channels of double-Higgs production at the ILC.

Table 1: Measurement uncertainties of the top quark Yukawa coupling in the SiD and ILD detector concepts. The simulation studies were carried out with detailed detector simulation taking into account the dominant machine-induced backgrounds.

Detector			ILD		SiD	
		Before cuts	After cuts			
			6 jets	8 jets	6 jets	8 jets
$t\bar{t}H$	4 jets	379	47	1	52	4
$t\bar{t}H$	6 jets	1572	520	164	479	144
$t\bar{t}H$	8 jets	1632	5	914	4	749
$t\bar{t}H$	other	2615	25	63	30	38
$t\bar{t}Z$		13331	315	651	264	468
$t\bar{t}b\bar{b}$		3586	314	557	250	452
$t\bar{t}$		772002	653	1284	580	954

Table 2: Summary of the precision achievable at the 500 GeV and 1 TeV stages of the ILC program, as well as the complete program.

Analysis	Polarization Luminosity	Precision coupling y_t
$t\bar{t}H$(500 GeV)	(−0.8, +0.3) 1.6 ab^{-1}	≈ 9%
$t\bar{t}H$(1 TeV)	(∓0.8, ±0.2) 1.0 ab^{-1}	4.3% – 4.5%
HiLumi scenario	500 GeV (−0.8, +0.3) + 1 TeV (−0.8, +0.2)	≈ 2%

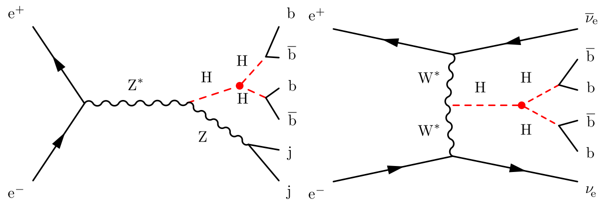

Figure 4: Feynman diagram of the processes $e^+e^- \to HHZ$ with subsequent hadronic decay of the Z boson, and $e^+e^- \to HH\nu\bar{\nu}$. In either case the Higgs bosons decay via $H \to b\bar{b}$.

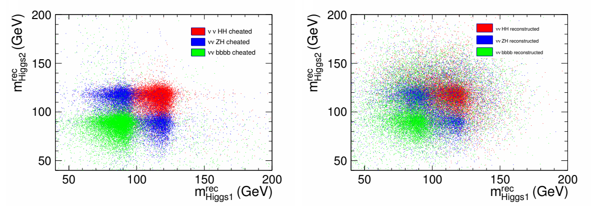

Figure 5: (Left) Two-dimensional distribution of the reconstructed Higgs masses using perfect reconstruction (Right) Two-dimensional distribution of a realistic simulation of the reconstructed Higgs masses in an ILC detector.

3. Measurement of the Higgs tri-linear self-coupling

The dominant Feynman diagrams for processes of double Higgs production sensitive to the tri-linear Higgs self-coupling are shown in Figure 4. Additional diagrams that are not sensitive to this coupling contribute to the production of double Higgs events, complicating the extraction of the coupling from the observed cross section. The interference between the diagrams is constructive for ZHH at 500 GeV and destructive for $\nu\bar{\nu}$HH at 1 TeV.

Key to the successful reconstruction of the complex final states is a highly performing reconstruction. Figure 5 shows how a realistic simulation (right panel) compares to a perfect reconstruction (left panel) of double Higgs events and the dominant background channels. There is room for further background rejection and hence precision improvement by reducing confusion in jet clustering. The details of the analyses of different signatures of double Higgs production with subsequent decay $H \to b\bar{b}$ is shown in Table 3. The achievable precision at different stages of the ILC program, including earlier stages, and a possible improvement by adding the $H \to WW^*$ final state is summarized in Table 4.

Table 3: Measurements of the strength of the tri-linear Higgs self-coupling and the cross section of various channels containing two Higgs boson in associated production at the ILC with $\sqrt{s} = 500$ GeV and an integrated luminosity of 1.6 ab^{-1}

channel	# events		significance	
ZHH $\to$	signal	bg	XS $\times \mathcal{BR}$	coupling y_t
$e^-e^+b\bar{b}b\bar{b}$	1.9	3.2	0.84 σ	0.64 σ
$\mu^-\mu^+b\bar{b}b\bar{b}$	2.6	5.6	0.90 σ	0.74 σ
$\nu\bar{\nu}b\bar{b}b\bar{b}$	3.0	3.2	1.22 σ	1.09 σ
$b\bar{b}b\bar{b}b\bar{b}$	6.6	17.8	1.34 σ	1.29 σ
$q\bar{q}b\bar{b}b\bar{b}$	7.0	31.4	1.12 σ	1.06 σ

Table 4: Summary of the achievable precision of the measurement of the tri-linear Higgs self-coupling at various stages of the ILC program. Later stages take into account results from earlier stages. A possible improvement using the $H \to WW^*$ final state is still work in progress.

Analysis	Polarization	Precision on	
	luminosity	XS $\times \mathcal{BR}$	coupling
ZHH(500 GeV)	(−0.8, +0.3)	4.5 σ	66%
$HH \to b\bar{b}b\bar{b}$	1.6 ab^{-1}		
+ZHH(1 TeV)	(−0.8, +0.2)	7.2 σ	16%
+$\nu\bar{\nu}$HH			
$HH \to b\bar{b}b\bar{b}$	2.5 ab^{-1}		
+$HH \to b\bar{b}WW$	(in progress)	$\approx 9\,\sigma$	$\approx$ 13%

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