PROCEEDINGS OF SCIENCE

What Can Be Learnt From Higgs Studies at ILC

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The International Linear Collider (ILC) project is the most mature project for the future Higgs factory based on the technology of superconducting accelerating cavities. It offers plethora of measurements in the Higgs sector to address open questions of the Standard Model of particle physics and cosmology. Presented in this contribution are prospects for precision measurements of the Higgs properties at the ILC, including its exotic and CP violating interactions, the trilinear self-coupling as well as the sensitivity to new physics at large energy scales from global EFT fits based on Higgs observables.

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1. Introduction

The International Linear Collider (ILC) was proposed as a mature option for the future e^+e^- Higgs factory, which is considered as the highest priority next large infrastructure for the particle physics. The baseline running scenario for the staged ILC construction assumes starting at a centre-of-mass energy of 250 GeV followed by a 500 GeV stage [1]. In the assumed 22-year running period the ILC is expected to deliver the integrated luminosities of about 2 ab^{-1} at 250 GeV, 4 ab^{-1} at 500 GeV and 200 fb^{-1} at the top-quark pair-production threshold around 350 GeV. Additional 8 ab^{-1} can be collected at 1 TeV stage, which is considered as the possible upgrade. The design includes polarisation for both e^- and e^+ beams, of 80% and 30%, respectively, which is the unique feature of the ILC. Polarisation is crucial for many precision measurements, direct and indirect BSM searches, as well as for control of systematic effects. Two detector concepts, ILD and SiD, have been developed for the ILC [2, 3], both optimised for the Particle Flow reconstruction.

2. Higgs at 250 GeV ILC

For centre-of-mass energies up to about 450 GeV, the Higgsstrahlung process, Higgs boson production together with Z boson, dominates the Higgs boson production at e^+e^- collisions, see Fig. 1 (left). In this channel we can use "Z-tagging" approach for unbiased selection of Higgs production events, i.e. making no assumptions about the Higgs boson decays. Figure 1 (right) shows the recoil mass distribution for Higgsstrahlung events and SM background processes, for a Z boson decaying into a muon pair at the initial ILC stage [5]. Higgsstrahlung process allows for a model independent determination of the Higgs boson couplings. Recoil mass technique results also in high sensitivity to rare and exotic (including invisible) Higgs boson decays. From direct search at 250 GeV, limit of 0.23% is expected on the invisible Higgs decays branching ratio [6]. The global fit of the Higgs observables and other precision electroweak measurements can be performed in the framework of the Standard Model effective field theory (SMEFT). Even in this most general

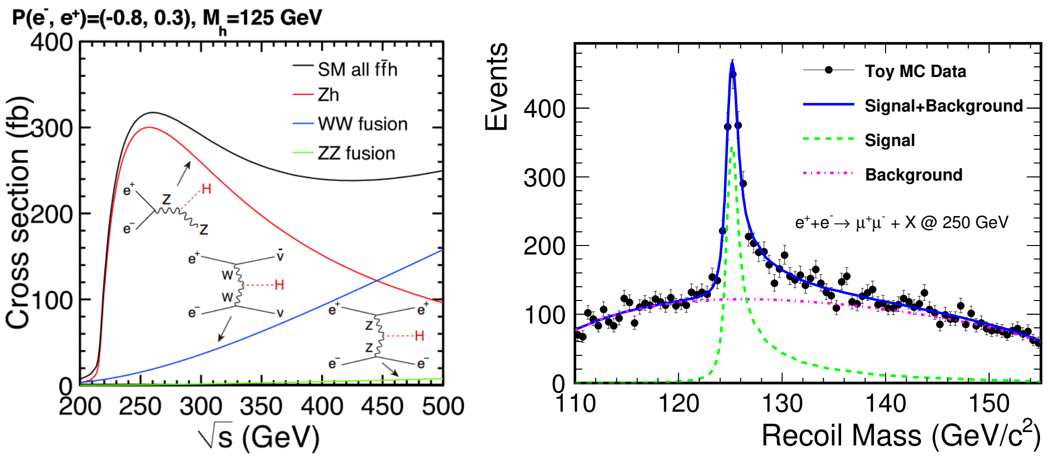


Figure 1: Higgs production at the ILC. Left: cross sections for the three major production processes as a function of collision energy [4]. Right: recoil mass spectrum for signal of Higgs boson production and SM background at 250 GeV ILC, for $Z \to \mu^+\mu^-$ selection [5].

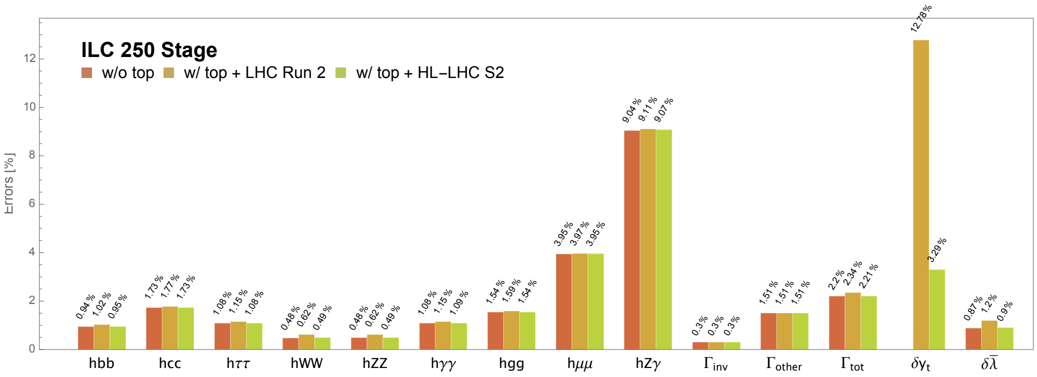


Figure 2: Global fit results for the Higgs couplings, for the ILC running at 250 GeV [7]. Included in the fit are electro-weak precision observables from LEP and SLC, as well as rare Higgs branching ratios and top ameasurements from the LHC.

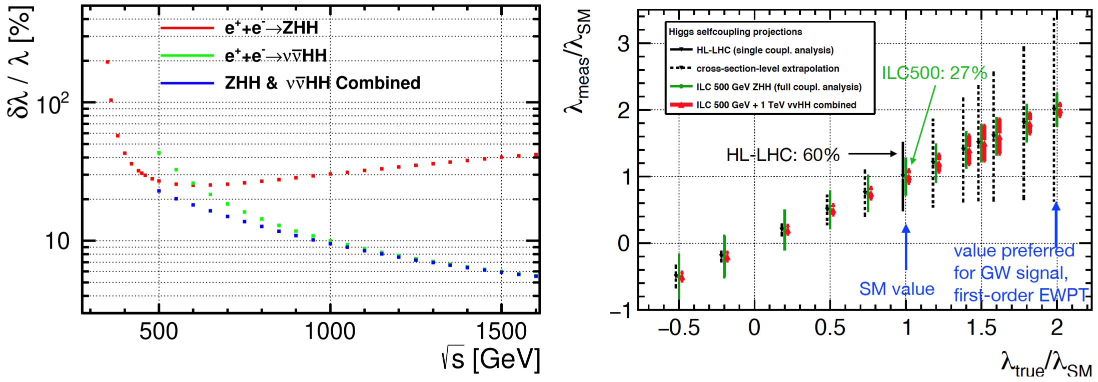


Figure 3: Estimated precision on the determination of the Higgs self-coupling λ from the measurement of the double Higgs production: as a function of the centre-of-mass energy (left) and as a function of the coupling modification factor (right).

approach, sub-percent level precision of Higgs coupling measurement is obtained already at the first energy stage of the ILC, see Fig. 2. Direct measurement of top Yukawa coupling and Higgs self-coupling is only possible at higher energy stages.

3. Higgs at higher energy stages

Measurement of the Higgs boson self-coupling is a crucial test of the Standard Model and of the electroweak symmetry breaking mechanism in general. The coupling can be constrained using indirect measurements at 250 GeV but model-independent coupling determination is only possible by direct measurement of Higgs pair production processes involving the trilinear coupling at the tree level. Two processes contribute: double Higgs boson production in the Higgsstrahlung-like process, $e^+e^- \to ZHH$ which dominates at 500 GeV and double Higgs boson production in the WW-fusion process, $e^+e^- \to HH\nu\bar{\nu}$, which becomes important at high energies, see Fig. 3 (left). Expected precision of the Higgs self-coupling measurement from the ZHH process at 500 GeV ILC is shown in Fig. 3 (right) as a function of the actual coupling strenght. High precision of

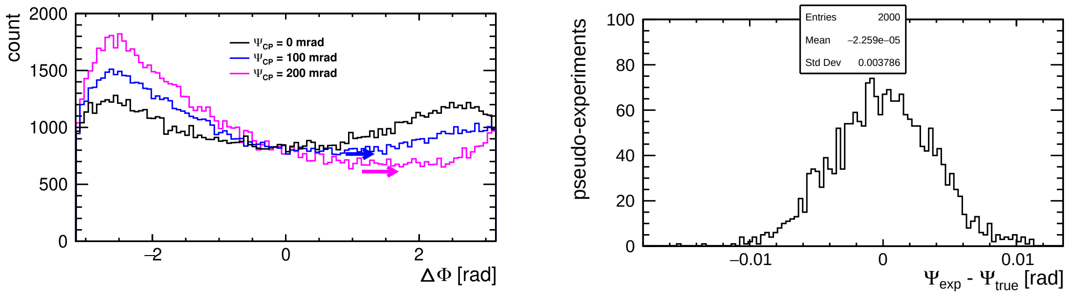


Figure 4: Left: distribution of the azimuthal angle between electron and positron scattering planes for different values of the phase describing CP mixing in the Higgs couplings. Right: statistical dissipation of the CP phase value extracted from the azimuthal distribution.

the coupling measurement at the ILC is preserved also for BSM scenarios with large self-coupling modification.

ILC upgrade to 1 TeV will open a unique possibility to test possible CP violation in the Higgs boson couplings to the gauge bosons. The observed 125 GeV Higgs mass eigenstate could be a mixture of CP-even and CP-odd states. Constraints on the CP mixing phase can be set from the analysis of the Z boson fusion process $\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}H$, as distribution of the azimuthal angle between electron and positron scattering planes is highly sensitive to this phase. As symmetric azimuthal distance distribution is expected for the CP conserving scenario, assymmetry and shift in the distribution minima position are a clear signatures of the CP violation, see Fig. 4 (left) [8]. Mixing angle can be measured with statistical uncertainty of 3.8 mrad (assuming small deviations from SM), which corresponds to the precision on the CP parameter f_{CP}^{HZZ} of $1.44 \cdot 10^{-5}$. This measurement is complementary to the measurements of the CP mixing in the fermionic couplings, which are accessible at lower energies [9].

4. BSM sensitivity

The precision of Higgs boson coupling measurements at subsequent ILC stages, for model-independent analysis approach, is summarised in Fig. 5 (left) [10]. The Standard Model gives exact predictions on these couplings, while sizable deviations are expected in most BSM scenarios, in particular in those with extended Higgs sector. Example of the possible deviation pattern is presented in Fig. 5 (right) [11]. The precision of the ILC measurements should clearly allow discrimination between the SM expectations and other models of "new physics" from the global analysis of the Higgs boson couplings. This is also illustrated in Fig. 6 for the ILC running at 250 GeV and for the combined 250 GeV and 500 GeV data, for BSM models difficult to access at the HL-LHC [12].

All measurements of Higgs boson production and other precision measurements of the relevant SM processes, can be combined in a general analysis based on the effective field theory (EFT) approach to put constraints on possible BSM effects coming from new physics at large energy scales. Expected constraints on the operator coefficients, from the fit to the 250 GeV and 500 GeV ILC data, are presented in Fig. 7 [7]. One can conclude that precision measurements at the ILC are sensitive to the possible new physics at $\mathcal{O}$(100 TeV) mass scales.

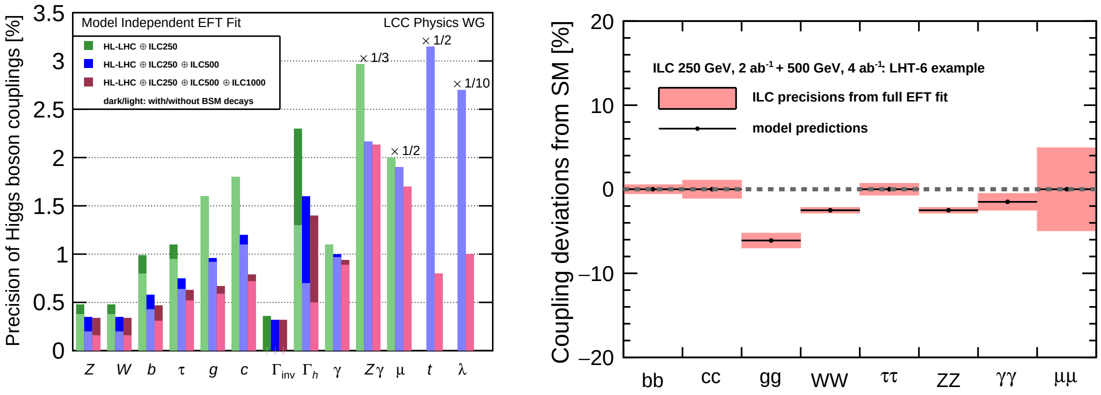
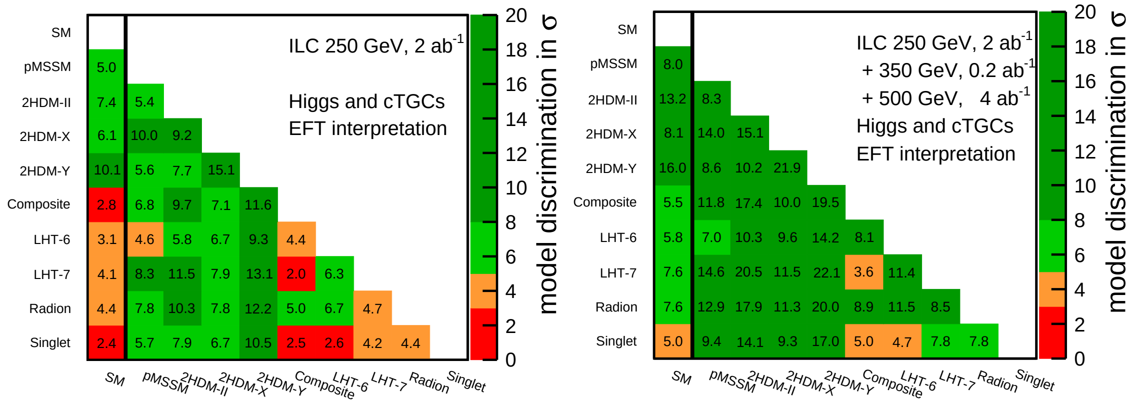


Figure 5: Left: precision of the Higgs couplings determined in a model-dependent fit, estimated for ILC [10]. Right: deviations of Higgs couplings from the SM predictions for the Little Higgs model with T-parity, compared to the uncertainties in the measurements expected from a fit to ILC data at 250 and 500 GeV [11].



ILC 250 GeV, 2 ab^{-1}

	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	5.0									
2HDM-II	7.4	5.4								
2HDM-X	6.1	10.0	9.2							
2HDM-Y	10.1	5.6	7.7	15.1						
Composite	2.8	6.8	9.7	7.1	11.6					
LHT-6	3.1	4.6	5.8	6.7	9.3	4.4				
LHT-7	4.1	8.3	11.5	7.9	13.1	2.0	6.3			
Radion	4.4	7.8	10.3	7.8	12.2	5.0	6.7	4.7		
Singlet	2.4	5.7	7.9	6.7	10.5	2.5	2.6	4.2	4.4	

ILC 250 GeV, 2 ab^{-1} + 350 GeV, 0.2 ab^{-1} + 500 GeV, 4 ab^{-1}

	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	8.0									
2HDM-II	13.2	8.3								
2HDM-X	8.1	14.0	15.1							
2HDM-Y	16.0	8.6	10.2	21.9						
Composite	5.5	11.8	17.4	10.0	19.5					
LHT-6	5.8	7.0	10.3	9.6	14.2	8.1				
LHT-7	7.6	14.6	20.5	11.5	22.1	3.6	11.4			
Radion	7.6	12.9	17.9	11.3	20.0	8.9	11.5	8.5		
Singlet	5.0	9.4	14.1	9.3	17.0	5.0	4.7	7.8	7.8	

Figure 6: Expected discrimination power of the Higgs boson coupling fit for the Standard Model and different BSM scenarios for, ILC at 250 GeV (left) and for combined 250 GeV and 500 GeV data (right) [12].

5. Conclusions

Precise determination of Higgs parameters is crucial for validation of the Standard Model or any alternative BSM theory. With high measurement precision, beam polarization and clean experimental environment, per mile level coupling measurements at the ILC will be sensitive to BSM scales of $\mathcal{O}$(100 TeV). At higher energy stages Higgs self-coupling measurement to around 10% is possible. Presented studies were based on the full simulation results for the ILD baseline design. Significant improvement is still expected from studies ongoing within the ECFA study on e^+e^- Higgs/Top/EW factory, taking into account new detector options currently considered and new analysis tools. Many new or updated results are expected to be presented in the study report.

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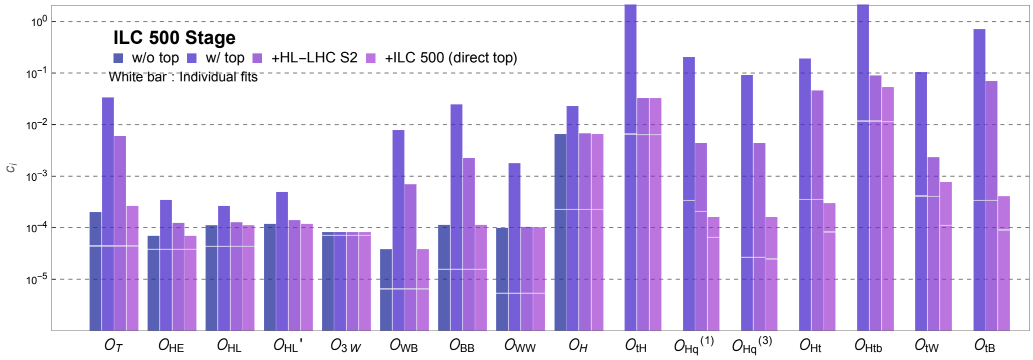

Figure 7: Global-fit results for the ILC running at 250 GeV and 500 GeV. Presented are the 1σ bounds on the operator coefficients, renormalized at $\Lambda = 1$ TeV.

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