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Highlights of the Higgs precision program at ILC

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With technically mature design and well understood physics program, ILC is a realistic option for realization of a Higgs factory. With a unique physics reach of a linear collider, ILC meaningfully complement projections for HL-LHC. Energy staged data collection, flexible beam polarization and capability to reach a TeV center-of-mass energy enable unique precision to probe BSM models above the discovery limit as well as to measure the Higgs self-coupling. These and other highlights from the ILC Higgs physics program will be discussed.

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1. Introduction

The very existence of the Higgs boson opens several important questions on the nature of relativistic vacuum, in addition to the role Higgs boson may play in realization of New Physics (BSM). International Linear Collider (ILC) [1] operating as an electroweak/Higgs/top factory and beyond up to 1 TeV center-of-mass energy, as it will be argued in this paper, will bring significant added value to the projected HL-LHC sensitivities in the Higgs sector. Among others, ILC operating at 250 GeV and 500 GeV will enable above 5σ discrimination of BSM models inaccessible at HL-LHC. Linear colliders, namely ILC being capable to reach TeV center-of-mass energies, significantly extends sensitivity of the future Higgs factories to measure the Higgs self-coupling as a shaping parameter of the vacuum potential. Through Higgs invisible and exotic decays extended Higgs sector can be probed, including connections to Dark Matter.

2. Higgs couplings and the self-coupling

Higgstrahlung (HZ) at 250 GeV ILC will result in production of half a million Higgs bosons in 1 ab^{-1} of collected data, enabling measurements of the Higgs branching ratios down to values of order 10^{-4}. By counting recoiled Z bosons, absolute measurement of the HZ cross section can be made to further translate into absolute normalizations of the Higgs partial widths. Model independent measurements of Higgs couplings in HZ complement model dependent measurements in the κ-framework and altogether serve as the input to Effective Field Theory (EFT) global fits. In Figure 1 [2], projections of the SMEFT fit on Higgs couplings and anomalous trilinear gauge couplings (aTGCs) are given for ILC (green) and other future colliders. Clear improvement in precision w.r.t. the HL-LHC is visible, as well as the advantage of the energy-staged approach and, in particular, of the operation at the highest center-of-mass energy.

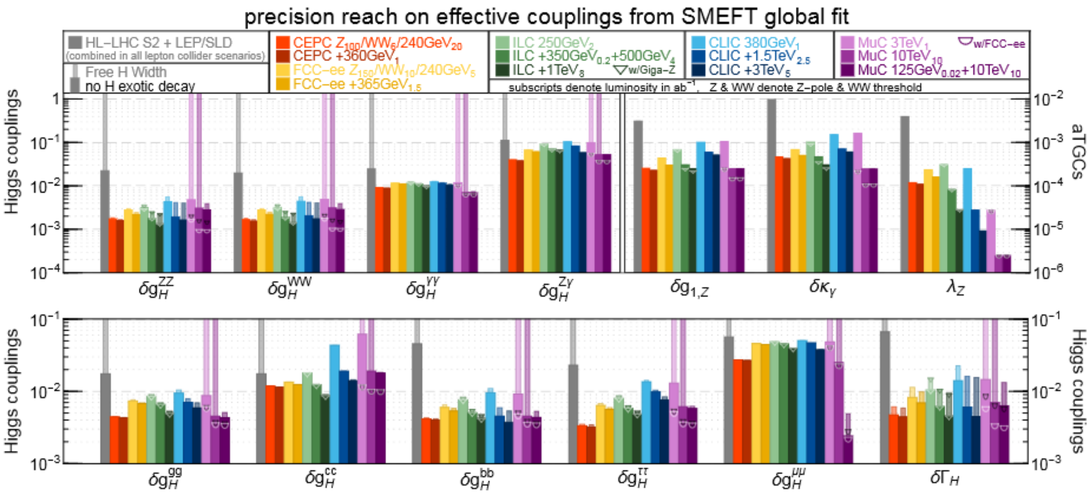

Figure 1: Relative statistical precision of the Higgs and aTGCs couplings in the SMEFT global fit, for ILC (green) and other future colliders [2].

There are two complementary double-Higgs production processes available at center-of-mass energies of at least 500 GeV: $e^+e^- \rightarrow ZHH$ (double Higgsstrahlung) and $e^+e^- \rightarrow \nu\nu HH$ (WW-fusion). If the self-coupling (λ) takes the Standard Model (SM) value, then double Higgsstrahlung can be observed at center-of-mass energy of 500 GeV with a significance of 8σ, combining the HH→4b and HH→bbWW* channels. This would translate into a relative statistical precision of λ of ~27% [1]. Addition of ILC run at 1 TeV center-of-mass energy will improve λ determination to a relative precision of 10%, from the double-Higgs production cross-section measurement. The above clearly illustrates superiority of an e^+e^- collider operation at the highest center-of-mass energy in the Higgs self-coupling determination. Table 1 illustrates projections of the Higgs self-coupling relative statistical precision if it takes the Standard Model value, in the 68% confidence level limit [3]. If however λ significantly deviates from the SM prediction, high energy linear e^+e^- collider will be particularly sensitive to it, in comparison to a proton-proton collider (i.e. HL-LHC). This is illustrated in Figure 2.

collider	di-Higgs	
	(1) excl.	(2.a) glob.
HL-LHC	$^{+60}_{-50}$% (50%)	52%
HE-LHC	10-20% (n.a.)	n.a.
ILC_{250}	–	–
ILC_{350}	–	–
ILC_{500}	27% (27%)	27%
ILC_{1000}	10% (n.a.)	10%
$CLIC_{380}$	–	–
$CLIC_{1500}$	36% (36%)	36%
$CLIC_{3000}$	$^{+11}_{-7}$% (n.a.)	n.a.
$FCC\text{-}ee_{240}$	–	–
$FCC\text{-}ee_{365}$	–	–
$FCC\text{-}ee^{4IP}_{365}$	–	–
FCC-eh	17-24% (n.a.)	n.a.
FCC-ee/eh/hh	5% (5%)	6%
LE-FCC	15% (n.a)	n.a
CEPC	–	–

Table 1: Relative statistical precision to measure SM predicted value of λ, at 68% CL limit. Columns (1) and (2) correspond to collaborations' input to [3] and the Higgs@FC WG estimates.

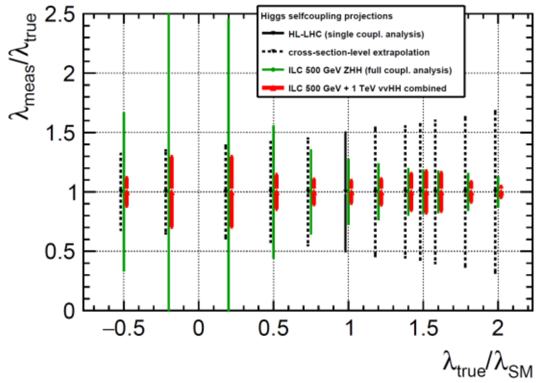

Figure 2: Relative statistical precision of λ at 1 TeV ILC and at HL-LHC, if λ deviates from the SM prediction.

3. Probing BSM in the Higgs sector

Precision of the Higgs couplings to be achieved ILC will translate to the sensitivity to probe realizations of BSM models, even ones inaccessible or hardly accessible at HL-LHC. Graphical representation of the χ^2 separation between SM and a list of models mentioned above is illustrated in Figure 3 [4]. It is clear that ILC operating already up to 500 GeV will be able to confirm realization of such BSM models beyond the 5 σ discovery limit.

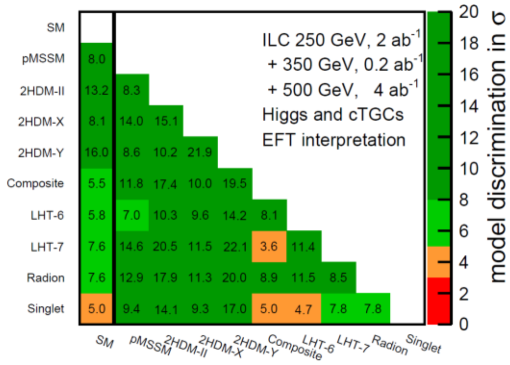

Figure 3: χ^2 separation in σ, between SM and BSM models hardly accessible at HL-LHC, derived from the EFT fit of Higgs couplings and aTGCs at various ILC energy stages [4].

3.1 Exotic Higgs decays

Higgs invisible decays are of particular interest to establish connectons of the Higgs sector with WIMP Dark Matter. Such possiblities are established in BSM models with the extended Higgs sector, including the possibilty of exotic Higgs decays to scalar mediators (φ) in the mass range between 10 GeV and 60 GeV. In the full simulation of ILD detector operating at 250 GeV center-of-mass energy ILC, 10^{-3} upper limit on BR($H\rightarrow\varphi\varphi$) can be set with the 95% CL limit. Figure 4 [5] illustrates reconstruction of scalar mediators employing the recoil mass technique in the case of φφ decaying to 4 b-jets. Similar approach is applicable for scalar mediators invisible decays. The study on the latter is ongoing.

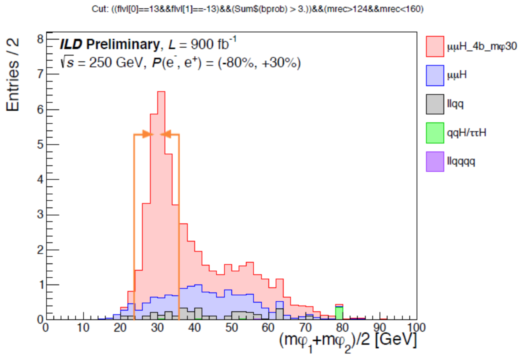

Figure 4: Di-boson (φφ) mass reconstruction for m_φ=15 GeV, employing recoil mass technique at 250 GeV ILC [5].

3.2 CP violation in the Higgs sector

Staged realization of ILC (a linear e^+e^- collider) enables numerrous HXX bosonic and fermionic vertices to be probed for CP violation (CPV) in the Higgs production and decays. This is illustrated in Table 2.

fermion couplings	
$H \to \tau^-\tau^+$	250+ GeV
$e^-e^+ \to Ht\bar{t}$	500+ GeV
boson couplings	
$e^-e^+ \to HZ$	250+ GeV
$H \to ZZ$	250+ GeV
$H \to WW$	250+ GeV
$e^-e^+ \to He^-e^+$ (ZZ-fusion)	1000+ GeV

Table 2: Higgs production and decay mechanisms available at ILC to probe the CP violating mixing in the Higgs sector.

CPV in the Higgs sector can be probed either trough measurement of the effective g^{eff}_{HX} couplings in the EFT framework or via reconstruction of CP sensitive angular observables. Both can equally probing CPV realization of the Higgs mass eigenstate as a mixture of CP-odd and CP-even states via mixing angle Ψ_{CP}. In both cases, CP sensitive parameter f^{CP}_{HX} can be defined as:

$$f^{CP}_{HX} = \Gamma^{CP\text{-}odd}(H\rightarrow XX)/(\Gamma^{CP\text{-}odd}(H\rightarrow XX) + \Gamma^{CP\text{-}even}(H\rightarrow XX))$$

providing a common ground for interpretation of various CPV measurements in the Higgs sector [6]. Connection of f^{CP}_{HX} with the CP violating mixing angle Ψ_{CP} between CP-odd and CP-even states is provided via:

$$f^{CP}_{HX}=sin^2\Psi_{CP},$$

while the effective Higgs coupling g^{eff}_{HX} is naturally defined [6] as:

$$g^{eff}_{HX}=(\Gamma^{CP\text{-}odd}(H\to XX)+\Gamma^{CP\text{-}even}(H\to XX))/\,\Gamma^{SM}(H\to XX)$$

Projections have been mostly made for the Higgs to ττ decays since the CPV effect occurs at the Born level in Higgs to fermion interactions and should be visible with f^{CP}_{HX} precision of the order of 10^{-2} or better [6]. Figure 5 [7] illustrates example of such measurement at 250 GeV ILC, demonstrating the feasibility of 10^{-2} precision of $f^{CP}_{H\tau}$ determination with 0.9 ab^{-1} of $e^-_L e^+_R$ polarized data. Estimated precisions of CPV measurements at various future experiments are summarized in Table 3 [6]. It's worth mentioning that there is ongoing analysis at 1 TeV ILC of the achievable precision of CPV mixing angle measurement in the bosonic HZZ vertex, where the Higgs bosons are produced in ZZ-fusion. As indicated in Table 3, CPV Higgs interactions with vector bosons (V) require higher precision of f^{CP}_{HV} measurement as they occur at the loop level.

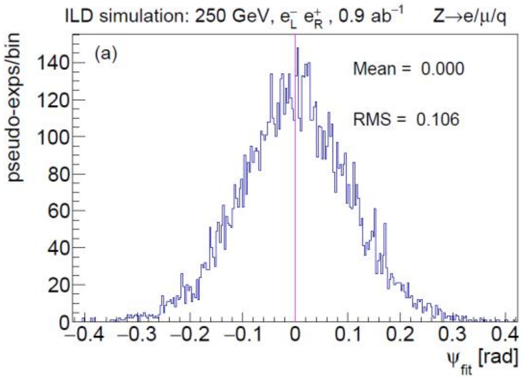

Figure 5: Illustration of 250 GeV ILC precision to measure CP violating mixing angle Ψ_{CP} in $H\to\tau^+\tau^-$ decays. As documented in [7], the overall combined precision of measurements with various data polarization results in 75 mrad of the absolute statistical uncertainty of Ψ_{CP}, corresponding to $5.6\cdot10^{-3}$ precision of $f^{CP}_{H\tau}$.

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000		125	125	≥ 500	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	20,000	250	350	500	1,000		250			
HZZ/HWW	$4\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.4\cdot10^{-4}$	$1.1\cdot10^{-4}$	$4\cdot10^{-5}$	$8\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	∼1	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	–	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

Table 3: Projections on precision of f^{CP}_{HX} determination at various future experiments. Check mark indicates feasibility of such a measurement [6].

4. Summary

ILC is a viable, mature and technologically available option for a future Higgs factory. With a QCD background-free experimental environment of an e^+e^- collider, flexible polarization of both beams and upgradeable center-of-mass energy, ILC Higgs physics program offers competitive measurements of the Higgs couplings as a probe of BSM physics beyond the discovery limit, self-coupling measurement with a precision unique to a high-energy linear collider (10% of the relative statistical uncertainty or better), plethora of CPV measurements in the Higgs production and decay vertices and many more. Ongoing efforts on improvement of the reconstruction and identification algorithms indicate feasibility of further enhancements in precision.

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