PROCEEDINGS OF SCIENCE

Linear electron-positron colliders as future Higgs factories

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Linear electron-positron colliders are viable options for realization of future Higgs factories. With a unique physics reach, they meaningfully complement projections for both HL-LHC and future circular hadron colliders. Energy-staged data collection, employment of beam polarization and capability to reach a TeV or above centre-of-mass energies enable unique precision to probe BSM models above the discovery limit as well as to measure the Higgs self-coupling. Among others, the above will be illustrated on examples from ILC and CLIC full-simulation studies.

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1. Introduction

Upon learning about the mass generation mechanism with the discovery of the Higgs boson in 2012, the state-of-the art in particle physics leaves numerous relevant questions opened: from the hierarchy and cosmological constant problems to the role Higgs boson might play in realization of Beyond the Standard Model physics (BSM). With no New Physics discovery at LHC and its limited resolution to probe Higgs properties, questions like how point-like the Higgs boson is or what is the exact shape of the Higgs potential can be answered with limited accuracy. The Higgs self-coupling parameter λ, determining the shape of the potential of the relativistic vacuum, can be probed at HL-LHC with 50% uncertainty [1]. Also, New Physics can be manifested in the Higgs sector in various ways, from extended Higgs sector with additional states, to a Higgs boson which is a CP violating mixture of scalar and pseudoscalar states. Often, such scenarios are beyond the discovery limit sensitivity of HL-LHC.

This call for machines (so called Higgs factories) that could individually or in combination with other ongoing and future experiments, explore in a most efficient way the physics at the energy frontier limit. Thus the European Particle Physics Strategy Update 2020 [2], brings Higgs factories are the highest priority future initiatives.

1.1 Unique features of linear colliders

All future Higgs factories are proposed as lepton (electron-positron) colliders introducing benefits from the well-defined inital state in almost QCD-free environment. In case of linar colliders (LCs), ILC [3] and CLIC [4], there are no limits from synchrotron radiation to reach above TeV center-of-mass energies. Due to linar design, LCs can operate as staged, upgradable machines where various Higgs production mechanisms are accessible over the energy scale span. This is illustrated in Figure 1. Enlarged statistics of numerous processes due to a rising cross-section with a center-of-mass energy, allows for less precise determination of an observable at high energy leading to the same precision on coupling as in the more precise measurement at low energy [5]. Also, higher center/of/mass energies grant access to the rare Higgs decay modes.

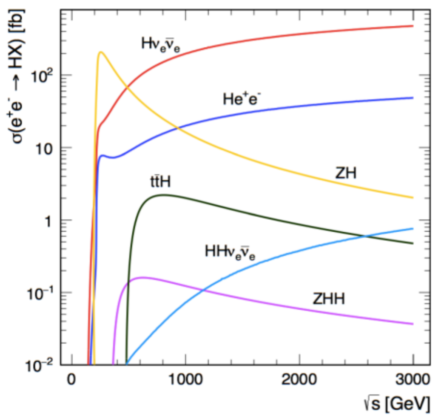

Figure 1. Various Higgs production mechanisms accessible at linear colliders.

$\sqrt{s} = 250$ GeV	$q\bar{q}H$	$\nu\bar{\nu}H$	ILC250	ILC250+500
L	34%	113%	23%	17%
R	36%	111%		
$\sqrt{s} = 500$ GeV	$q\bar{q}H$	$\nu\bar{\nu}H$	ILC500	
L	43%	37%	24%	
R	48%	106%		

Figure 2. Expected ILC precisions on Higgs to $\mu\mu$ branching fraction measurement for different production channels, beam polarizations and center-of-mass energies.

Possibility to have polarized beams (±80, ±30)% at ILC and ±80% for electron beam at CLIC, effectively doubles the integrated luminosity for the Higgs production in WW-fusion, providing at the same time observables sensitive to New Physics what helps characterization of the probed BSM models. It also brings down the overall statistical uncertainty in combination of individual, uncorrelated, less precise measurements. The power of such a combination is illustrated in Figure 2, on example of the Higgs to muon coupling $g_{H\mu\mu}$ measurement at ILC [6], at different center-of-mass energies, exploiting different Higgs production mechanisms and various combinations of left (-) and right-handed (+) polarized beams.

Accessibility of the highest center-of-mass energies (1 TeV at ILC and 3 TeV at CLIC) offers unique sensitivity to plethora of physics measurement. In the next sections we will try to argue that the high energy reach is the key feature of linear colliders w.r.t. their circular e^+e^- alternatives. Figure 3 by the European Strategy Group, gives one possible illustration of unrivaled 3 TeV CLIC sensitivity to probe the energy scale of 4-fermion contact interactions.

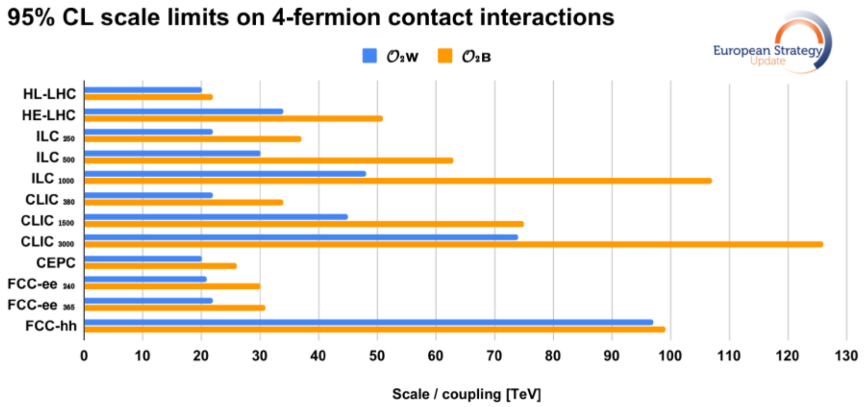

Figure 3. Comparison of future projects to probe the scale of 4-fermion contact interactions.

2. Why do we need an electron-positron linear collider?

It is fair to say that almost all future e^+e^- colliders, circular or linear, will complement HL-LHC measurements reducing, in combination, the statistical precision of the Higgs couplings down to a permille level (for most of the couplings). This is illustrated in Figure 4 [7]. The genuine advantages of LCs, in particular of their high-energy reach, with addition of polarization and insignificant dependence on theoretical uncertainties is illustrated on examples in the following sections.

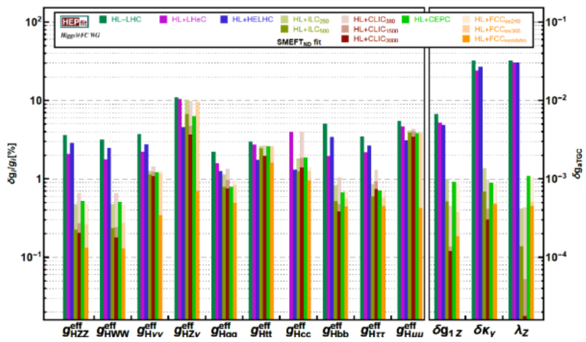

Figure 4. Estimated statistical precision of future projects to measure Higgs couplings in the SMEFT formalism.

2.1 Higgs self-coupling

The Higgs self-coupling λ is a critical parameter defining vacuum expectation v_0 value of the Higgs field as $v_0=m_H^2/2\lambda$. It further determines energy dencity of the Universe as $V_0=\lambda v_0^4/2$ implying possible connections of the Higgs field with the cosmological inflation. Also, λ can be strongly influenced by realization of BSM physics with even larger sensitivities than those of the Higgs to EW boson couplings. At linar colliders, λ can be masured in the double-Higgs production processes ZHH and ννHH at the highest available center-of-mass energies (see Fig.1). These processes exhibit different behavior to non-SM values of λ, removing the ambiguity existing if ννHH would be used solely. This is illustrated in Fig. 5 [5].

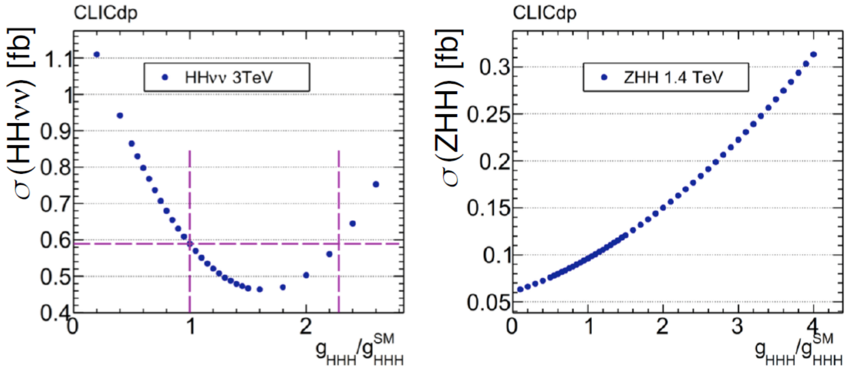

Figure 5. Illustration of the double-Higgs production cross-sections sensitivities to the Higgs self-coupling (here noted as g_{HHH}).

High achievable center-of-mass energies, together with the comparably insignificant theoretical uncetrainties (w.r.t. the hadron colliders), makes LCs a superior enviroment to measure λ. This is illustrated in Fig. 6 [7], showing unrivaled precision of 3 TeV CLIC to measure Higgs-self coupling, improved in combination with the measurement at the intermediate 1.4(5) TeV stage. At the other hand, projections for FCChh (also in Fig. 6) haevily rely on assumption of a drastic reduction of theoretical uncertainties (Parton Density Functions, higher-order calculations, non-perturbative approach, etc.) with respect to the current values.

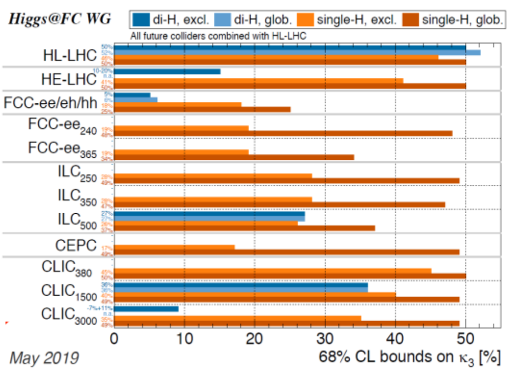

Figure 6. Projected precision of the future projects to measure Higgs self-coupling.

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Also, it is an interesting possibility that λ may significantly deviate from the SM-values. Again, capability of LCs to operate at TeV energies offer a clear advantage in terms of λ determination in such a case. This is illustrated in Fig 7 [8] for ILC.

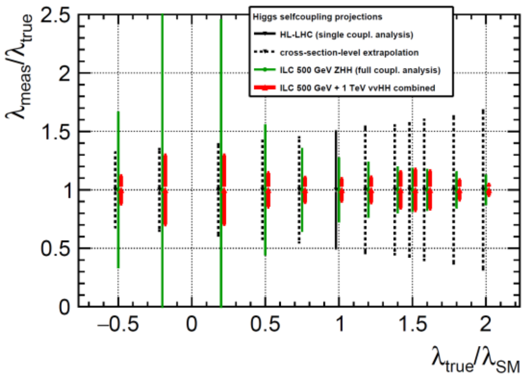

Figure 6. Enhancement of sensitivity to measure Higgs self-coupling strongly deviating from the SM-value, at the highest center-of-mass energies at ILC.

2.2 BSM in the Higgs sector

Realization of a particular BSM model will in most cases modify Higgs couplings to fermions and bosons at the level that can be probed at future linear colliders. Figure 7 [9] illustrates ILC at 250 GeV and ILC at 250 GeV and 500 GeV plus HL-LHC discrimination potential for various BSM models, mostly inaccessible at standalone HL-LHC. Apart from exhibiting complementarity of a LC to HL-LHC projections, Fig. 7 also illustrates advantage of data-staged approach in comparison to a single center-of-mass energy operation.

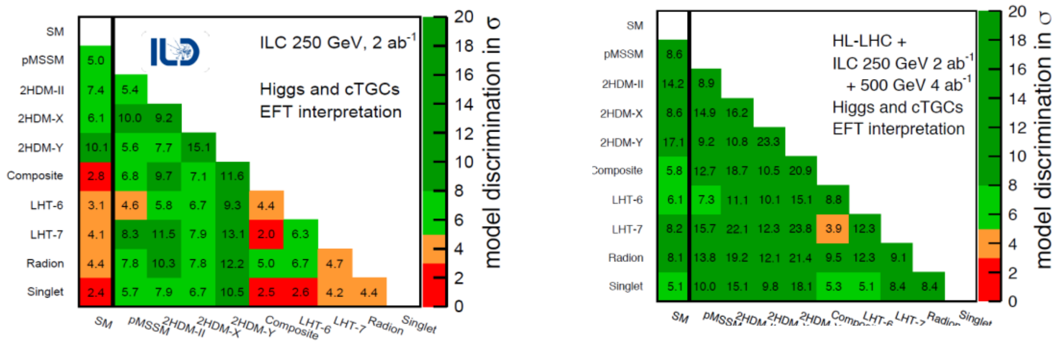

Figure 7. ILC (left) and staged ILC + HL-LHC sensitivity (right) to probe various BSM scenarios.

The New Physics can be manifested in the Higgs sector as modification of the Higgs boson properties itself, which, in example, could be either composite or a CP violating mixture of scalar and pseudoscalar states. Also, in most BSM models, Higgs sector is extended with additional states (singlet or doublet, light or heavy) that have to be probed at future colliders. Again, LCs operating at TeV center-of-mass energies (or above) offer the utmost sensitivity (in comparison to LHC and HL-LHC) to discriminate between such realization of New Physics models in the Higgs sector. This is illustrated in Figure 8 [1] on examples of 3 TeV CLIC capability to probe the Higgs compositeness scale and the mass scale of a heavy scalar singlet produced in association with the SM Higgs.

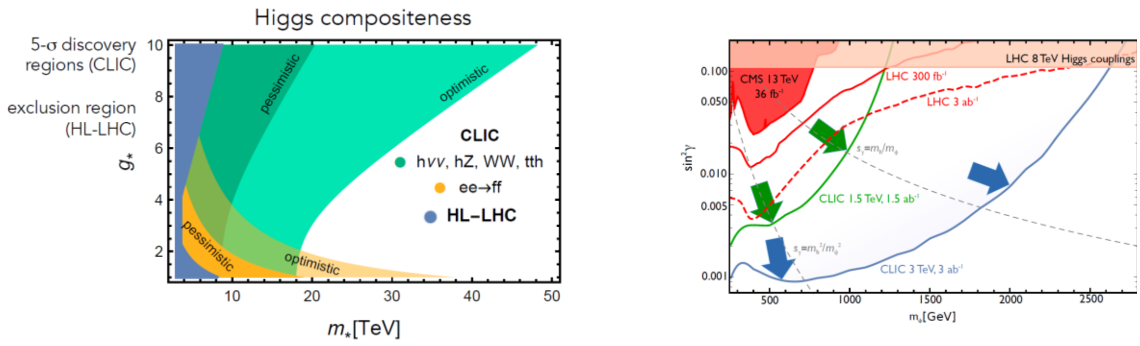

Figure 8. Illustration of a high energy LC (CLIC) to probe the Higgs compositeness scale (left) and the mass scale of a heavy singlet state produced in mixing (via mixing angle γ) with the SM Higgs boson.

3. Summary and outlook

With a unique capability to reach above TeV center-of-mass energies in almost QCD background free measurements and without strong dependences on theoretical uncertainties, future linear colliders offer high-precision measurements dominated by the statistical uncertainty. They have unrivaled sensitivity to probe the shaping parameter of the Higgs potential λ, as well as to discriminate, often beyond the discovery limit, BSM models otherwise inaccessible at HL-LHC. With these features LCs complement any future hadron machine (from HL-LHC to hadron-hadron circular colliders) enabling the utmost sensitivity of physics coverage at the energy frontier.

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