ILC Higgs Physics Potential

Shin-ichi Kawada (IPNS, KEK, Japan)

skawada@post.kek.jp

The International Linear Collider (ILC) is one of the proposed Higgs factories. In this contribution, we will discuss the potential of Higgs physics studies at the ILC, mainly based on Ref [1]. The evaluation of Higgs measurements was performed with full detector simulation of the International Large Detector (ILD) concept and/or Silicon Detector (SiD) concept [2].

The starting center-of-mass energy ($\sqrt{s}$) is 250 GeV, which is suitable for the precision Higgs measurements using Higgs-strahlung process ($e^+e^- \to Zh$). The $\sqrt{s}$ can upgrade up to 1 TeV enabling access to rare Higgs decays, Higgs self-coupling, as well as the BSM signatures in the Higgs sector. The beam polarization, 80% for electrons and 30% for positrons, helps us to improve the precision measurements.

The key measurement of the Higgs boson is the measurement of the absolute size of an inclusive cross-section σ_{Zh} using the recoil mass technique. Figure 1 left shows the Feynman diagram of $e^+e^- \to Zh$ with the decay of $Z \to \mu^+\mu^-$. Since the initial state of e^+e^- collision is well-known, the mass of the Higgs boson can be determined only by measuring muon momenta, without looking at any Higgs decay products. Figure 1 right shows the spectrum of the recoil mass taken from Ref. [3]. This recoil technique is also applicable for $Z \to e^+e^-$ and $Z \to q\bar{q}$ decay channel and has been analyzed in Refs. [3, 4]. Assuming the twenty years running scenario of the ILC with beam polarization sharing [5, 6, 7], the mass of the Higgs boson M_h can be measured with a precision of 14 MeV, σ_{Zh} can be determined with 0.7% precision, and the hZZ coupling g_{hZZ} can be measured with 0.4% relative statistical uncertainty.

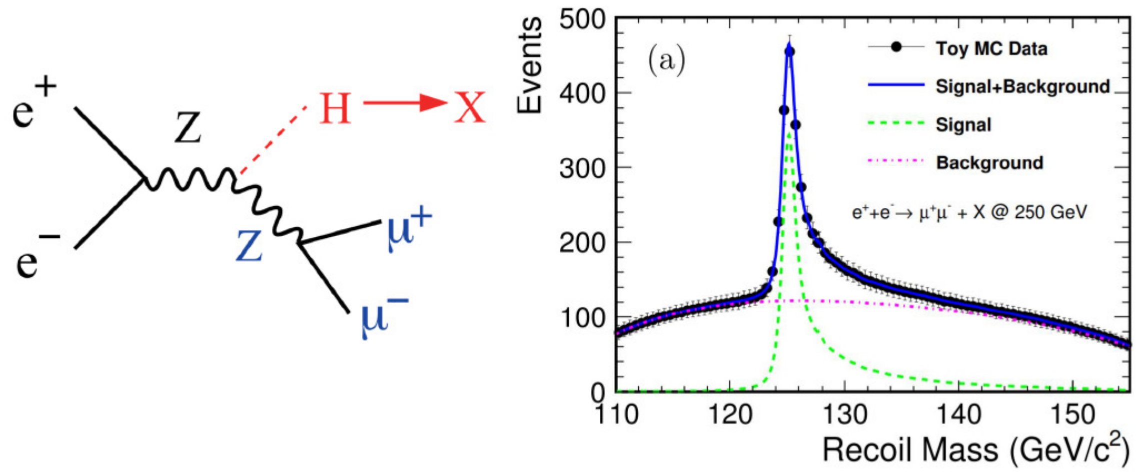

Figure 1: Left: Feynman diagram of $e^+e^- \to Zh$ with $Z \to \mu^+\mu^-$. Right: Recoil mass spectrum of events in the signal region 110-155 GeV at $\sqrt{s} = 250$ GeV. Taken from Ref. [3].

To extract Higgs boson couplings, we use dimension-6 SM Effective Field Theory (EFT) formalism. We use Higgs observables, triple gauge coupling observables, and electroweak precision observables as the inputs to the global fit under the EFT framework. We additionally use the ratio of branching ratio ($h \to \gamma\gamma$, ZZ^*, $Z\gamma$, and $\mu^+\mu^-$) from the HL-LHC prospects as the inputs. Details of the precisions of observables and EFT framework can be found in Refs. [1, 8, 9]. Here, we only present the important remarks and results. The Lagrangian used in this EFT framework is Lorentz invariant, gauge invariant, and CP conserving. Though this Lagrangian has 23 free parameters, it is possible to determine all these parameters simultaneously. The Higgs couplings can be extracted in a highly model-independent way in the sense that all models of new physics are describable either by the addition of

Presented at the 30th International Symposium on Lepton Photon Interactions at High Energies, hosted by the University of Manchester, 10-14 January 2022.

local operators to the SMEFT or by the addition of invisible and exotic Higgs decays. We compare the capabilities of the ILC for precision Higgs measurements to those of the HL-LHC, and it is shown in Figure 2. Since the assumptions for extracting Higgs couplings are different at the LHC and the ILC, it is not easy to compare each other. We have included two additional assumptions in our EFT framework: assume no Beyond-Standard-Model decay of Higgs boson, and no anomalous couplings in hWW and hZZ. Even with scenario S1 (HL-LHC projections with CMS κ fit), HL-LHC CMS plus ILC250, most of the couplings can reach $\sim 1\%$ precision, and we can robustly claim discovery of deviations from the SM of the size generally expected in new physics models.

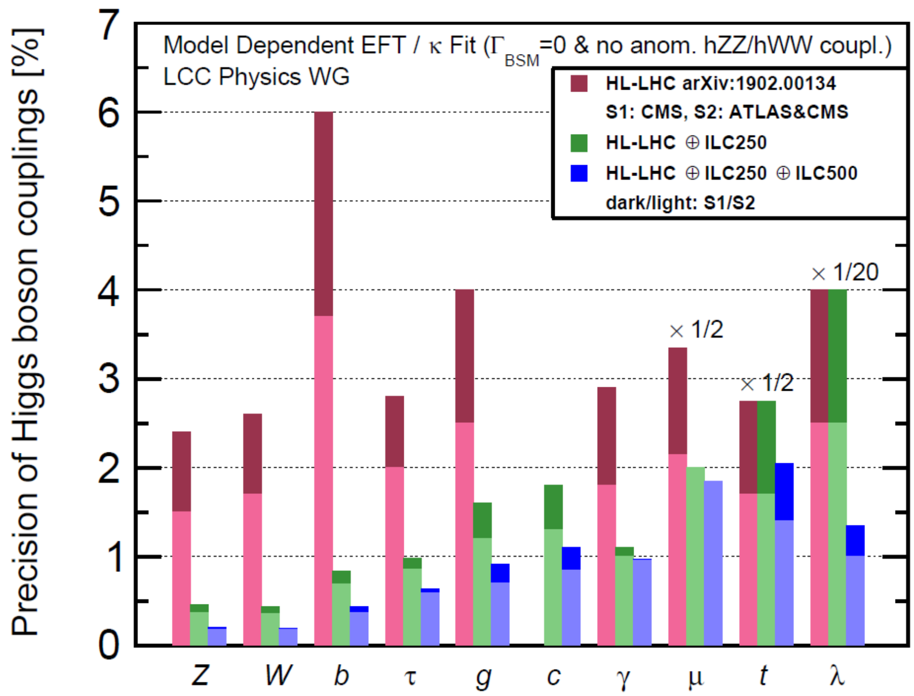

Figure 2: Projected Higgs boson coupling uncertainties for the LHC and ILC using the model-dependent assumptions appropriate to the LHC Higgs coupling fit. S1 is the HL-LHC prospects by CMS, and S2 is ATLAS and CMS. HL-LHC plus ILC S1 is the result based on current full simulation, and S2 is the expected result assuming improvements in analysis techniques and tools. Taken from Ref. [1].

Finally, we discuss the measurement of Higgs self-coupling at the ILC. The measurement of trilinear Higgs self-coupling is quite important because this measurement allows testing the Higgs mechanism by measuring the Higgs potential directly. However, this measurement is very challenging due to its small cross-section of the Higgs self-coupling and the interference between signal and background.

Full simulation studies are performed by using $e^+e^- \to Zhh$ process with $Z \to q\bar{q}/\nu\bar{\nu}/\ell^+\ell^-$ and $hh \to b\bar{b}b\bar{b}/b\bar{b}WW^*$ channels at $\sqrt{s} = 500$ GeV. With 4 ab^{-1} statistics, a precision of 16.8% can be achieved on the cross-section measurement of $e^+e^- \to Zhh$ [10, 11, 12]. Assuming the SM with one free parameter of the trilinear self-coupling, this corresponds to an uncertainty of 27% on that coupling. At $\sqrt{s} = 1$ TeV, the $e^+e^- \to \nu\bar{\nu}hh$ process becomes dominant double Higgs production channel. With 8 ab^{-1} data, the studies [11, 12, 13] show that, in the same context of varying the trilinear Higgs coupling only, this coupling can be determined to 10% in relative statistical uncertainty. However, these estimates are conservative since the improvements are expected because we have tools and techniques of flavor tagging, jet reconstruction, and kinematic fitting to reconstruct the Higgs self-coupling better than the used in the references [10, 11, 12].

Since some new physics models, in particular, electroweak baryogenesis models, predict large deviations of the trilinear Higgs coupling from the SM, it is important to see how the expected precisions would change in such cases. Figure 3 left shows the cross-sections of the two double-Higgs production channels as a function of the triple Higgs coupling λ, and Figure 3 right shows the expected precisions of λ at the ILC. Since the interference is different for the two reactions, constructive for $e^+e^- \to Zhh$ but destructive for $e^+e^- \to \nu\bar{\nu}hh$, these two reactions are complementary in determining λ. If λ is a factor of 2 larger than SM value, the $e^+e^- \to Zhh$ process gets very useful and provide $\sim 15\%$ precision for λ.

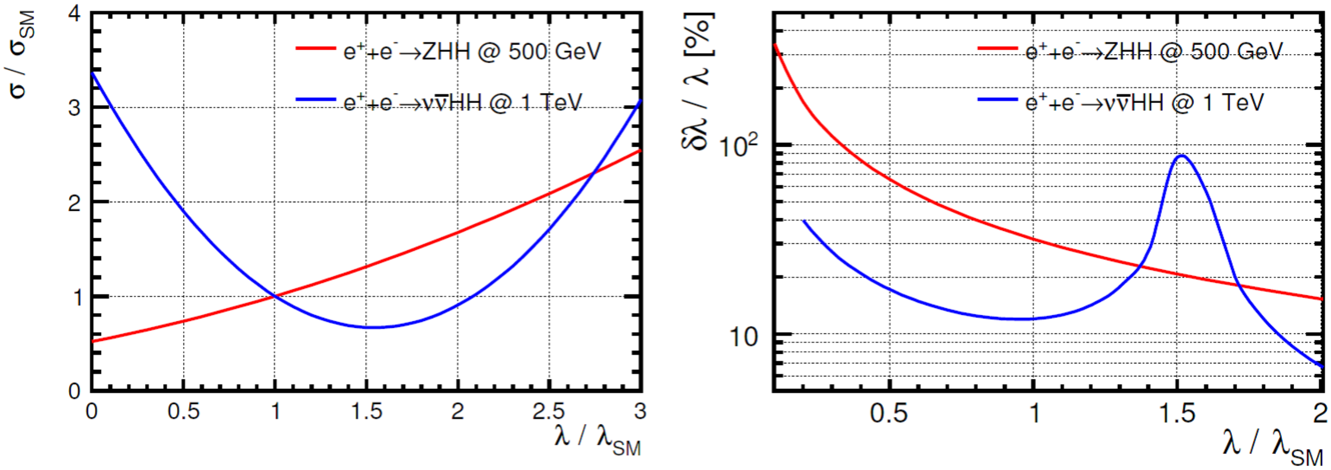

Figure 3: Left: the cross section as a function of λ for $e^+e^- \to Zhh$ and for $e^+e^- \to \nu\bar{\nu}hh$, where values of both λ and σ are scaled to their SM values. Right: expected precisions of λ when λ deviates from its SM value. Taken from Ref. [1].

References

[1] Philip Bambade *et al.*, The International Linear Collider — A Global Project, arXiv:1903.01629 (2019)

[2] Ties Behnke *et al.*, The International Linear Collider Technical Design Report Volume 4: Detectors, arXiv:1306:6329 (2013)

[3] J. Yan *et al.*, Measurement of the Higgs boson mass and $e^+e^- \to ZH$ cross section using $Z \to \mu^+\mu^-$ and $Z \to e^+e^-$ at the ILC, Phys. Rev. D **94**, 113002 (2016)

[4] M. A. Thomson, Model-independent measurement of the $e^+e^- \to HZ$ cross section at a future e^+e^- linear collider using hadronic Z decays, Eur. Phys. J. C (2016) **76**:72

[5] LCC Physics Working Group, Physics Case for the International Linear Collider, arXiv:1506.05992 (2015)

[6] ILC Parameters Joint Working Group, ILC Operating Scenario, arXiv:1506.07830 (2015)

[7] LCC Physics Working Group, Physics Case for the 250 GeV Stage of the International Linear Collider, arXiv:1710.07621 (2017)

[8] Tim Barklow *et al.*, Improved formalism for precision Higgs coupling fits, Phys. Rev. D **97**, 053003 (2018)

[9] Tim Barklow *et al.*, Model-independent determination of the triple Higgs coupling at e^+e^- colliders, Phys. Rev. D **97**, 053004 (2018)

[10] Claude Fabienne Dürig, Measuring the Higgs Self-coupling at the International Linear Collider, PhD thesis, DESY-THESIS-2016-027 (2016)

[11] Junping Tian, Study of Higgs self-coupling at the ILC based on the full detector simulation at $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1$ TeV, in Helmholtz Alliance Linear Collider Forum; Proceedings of the Workshops, Hamburg, Munich, Hamburg, 2010-2012, Germany (2013)

[12] Masakazu Kurata *et al.*, The Higgs Self Coupling Analysis Using The Events Containing $H \to WW^*$ Decay, LC-REP-2013-025 (2013)

[13] P. Roloff *et al.* (CLICdp Collaboration), Double Higgs boson production and Higgs self-coupling extraction at CLIC, arXiv:1901.05897 (2019)