The International Linear Collider (ILC): Research Potentials, Present Status and Future Plans

HITOSHI YAMAMOTO
DEPARTMENT OF PHYSICS, TOHOKU UNIVERSITY

ABSTRACT

In the new era of particle physics initiated by the Higgs boson discovery, a promising concept for an accelerator is seen in the proposed International Linear Collider (ILC). In this article, we review the physics case for the ILC, as well as its present status and future plans for its development.

INTRODUCTION

The discovery of the Higgs particle at the Large Hadron Collider (LHC) at CERN [1] opened a new era of particle physics. Even though we now have all of the ingredients of the Standard Model, or rather, because the spectrum is now complete, we are forced to face its remaining problems and questions. Some of those issues can be described as follows:

1. The radiative correction to the Higgs mass diverges quadratically. It indicates that there is new physics just beyond the current experimental energy scale, or that our universe is a very special one among many universes.
2. There exists no candidate for the dark matter in the Standard Model.
3. What caused the Higgs field to freeze at a certain value, giving masses to particles?
4. Are there more than one Higgs boson?
5. Is the Higgs boson elementary or composite?

Some of the themes above are related but an important feature is that in many of the models beyond the Standard Model, there exists a particle that looks just like the Standard Model Higgs particle with coupling constants to other particles only slightly different from those predicted by the Standard Model. Thus, it is imperative that the coupling constants of the Higgs particle be measured as precisely as possible.

Another area where deviation from the Standard Model may appear is related to the top quark, which is the heaviest particle in the Standard Model. And, of course, the most direct method to approach new physics is to detect particles not included in the Standard Model, which means that we must reach energies that are high enough for particles to be created on shell.

The advantages of a linear e^+e^- collider, such as the proposed ILC, are as follows:

1. Events are clean since it is a collision of elementary particles. Often all the particles of an event originate from the decay of a new particle itself without other particles to obscure the interaction.
2. One can control the 4-momentum of the initial state of the e^+e^- collision. This can be used, for example, to reconstruct a new particle by detecting particles recoiling against it.
3. One can control the polarization of the incoming beam. This allows direct probe to the gauge structure of the vertex creating the final state, and in some important cases, dominant backgrounds created by left-handed electron interactions can be turned off.

These features lead to impressive sensitivities in the Higgs and other physics, and also could lead to the ILC's capability to find new particles that might be missed at the upgraded LHC.

DESIGN

The ILC is currently envisioned as an energy-frontier e^+e^- collider, utilizing the most advanced designs. The ILC Technical Design Report [2] was published in June 2013. The ILC is anticipated to be based on superconducting acceleration technology, and the baseline ILC is to run at center-of-mass energies up to 500 GeV with an option to upgrade to about 1 TeV. The physics capabilities are summarized in Ref. [3,4]. The physics capabilities of the proposed ILC have also been extensively documented [2,5,6,7].

The ILC envisions two detectors that would use state-of-the-art technologies to achieve better momentum resolution by approximately a factor of 10, and better jet energy resolution by a factor of three, as compared to typical LHC detectors. These high resolutions could be realized in part by the relatively quiet environment of the linear collider and in part by developing new detector technologies.

PHYSICS

Higgs Physics

At an e^+e^- collider, Higgs particles are produced in two major processes. One is the 'Higgsstrahlung' process: $e^+e^- \to Zh$ that is dominant at lower energies; the other is the 'W fusion' process, which is dominant at higher energies. The cross sections of the two processes cross at around 450 GeV.

The Higgsstrahlung offers the use of the recoil mass technique; namely, by detecting the Z and calculating the invariant mass of the system recoiling against it, one can reconstruct the Higgs particle without actually detecting its decay products. A recoil mass distribution for the ILC running at 250 GeV is shown in Fig. 1. This allows an absolute determination of the Zh coupling. It also enables the measurement of the branching fraction of Higgs decaying to an invisible final state that can be detected to below 1% [4]. By the recoil mass technique, the Higgs mass can be determined with an error better than 30 MeV [4].

At a linear collider, one can separately reconstruct all major decay channels, such as a b pair, a W pair, a c pair, a τ pair, and a gluon pair. Once absolute branching ratios are measured as above, the Higgs total width is required to convert them to coupling constants, which can be obtained from the branching ratio to WW together with the decay rate to WW that is given by the W fusion production rate. With the full ILC dataset, the Higgs total width can be measured to 1.8% [4].

Fig. 2 shows the measurement accuracies of Higgs couplings [4]. The fit is performed assuming that the relative shifts from the Standard Model are the same for u, c, t, for d, s, b, and for e, μ, τ, and that the branching ratio to invisible or exotic final states is zero. The projected ILC values for the full dataset are shown with orange bars. The light green bars represent the 'conservative' projection for the High-Luminosity LHC where the systematics errors are assumed to be the same as now, while the dark green bars correspond to the case where the theoretical uncertainties are scaled by a factor of 1/2 while other systematic uncertainties are assumed to decrease at the same rate as the statistical errors [8].

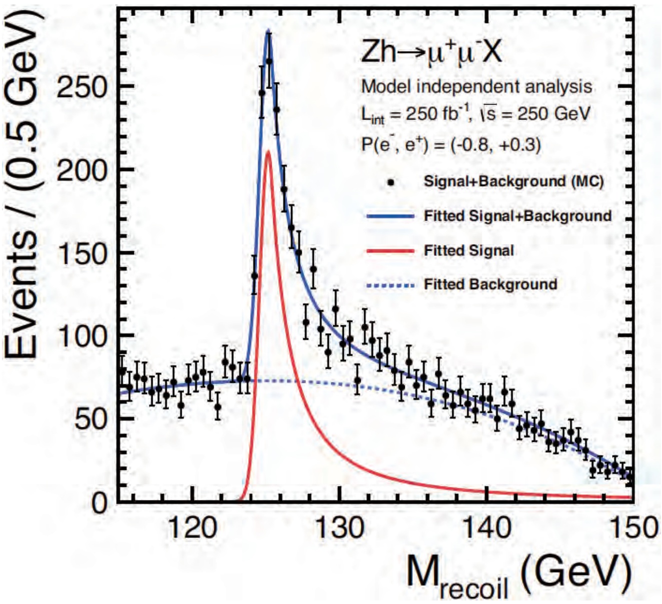

Fig. 1: Recoil mass distribution for $e^+e^- \to Zh$ where Z decays to $\mu^+\mu^-$.

The important point however, is that the linear collider could measure most of the major modes separately without the assumptions above. Projected measurement accuracies of Higgs couplings measured this way are shown in Fig. 3. The ILC with the full dataset could measure most of the couplings to 1% or better. This would be the level where many models of new physics could be distinguished.

The center of mass energy of 500 GeV is required for the measurement of Higgs coupling to top where ttH production is detected. It is worth noting that 500 GeV is only 30 GeV above the production threshold, and raising

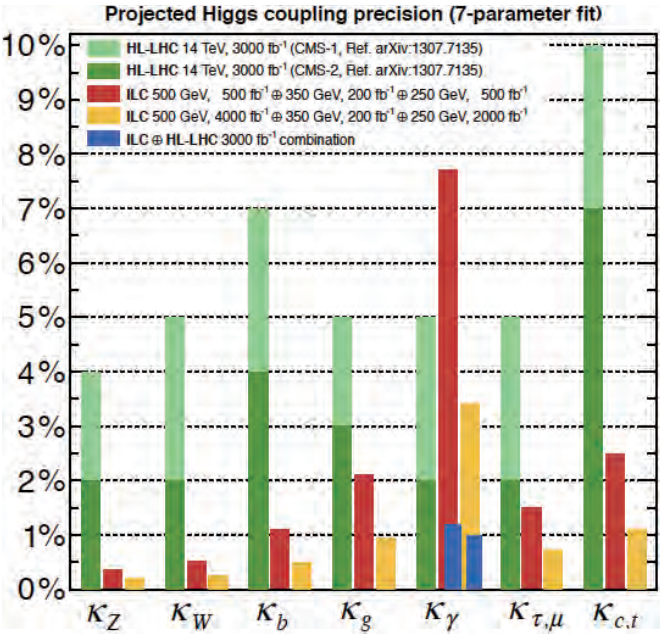

Fig. 2: Measurement accuracies of Higgs couplings. See the text for detail for the assumptions used for the fit.

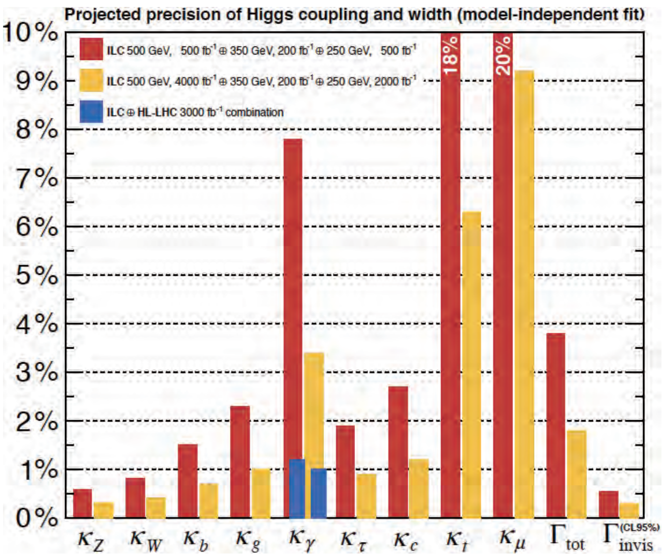

Fig. 3: The accuracies of the ILC's measurements of Higgs couplings without assuming generation universality or BSM final states.

the beam energy by 10% would increase the signal yield by a factor of 3 to 4 while the background would stay essentially the same. This would reduce the error on the Higgs coupling to top a by factor of 2 to 3% [4].

The Higgs self-coupling arises from the ϕ^3 term of the Higgs potential, which means that the Higgs potential is not symmetric with respect to the vacuum; namely, the Higgs self-coupling is a smoking gun for symmetry breaking. This is a challenging measurement at any facility. At a linear collider, final states with two Higgs particles are searched; it is desirable to perform the measurement at as high an energy as possible. At the 500 GeV ILC, the signal mode would be $e^+e^- \rightarrow Zhh$, and with the current state of the art technologies, the Higgs self-coupling is projected to be measured to 27% with the full dataset [4]. At 1 TeV, $e^+e^- \rightarrow \nu\nu hh$ mode could be detected to give the Higgs self-coupling to 16% with 2000 fb^{-1} of data [4].

Top Physics

At the ILC, top pair production could be studied either at the threshold or at higher energies. At the threshold, one could measure the top mass and width. The mass measured here would be closely related to the $\overline{MS}$ mass that is theoretically relevant. With 200 fb^{-1} of data taken near the threshold, the statistical errors on the top mass and width are estimated to be 17 MeV and 27 MeV [4], respectively. The top mass measured this way can be translated to the $\overline{MS}$ mass with a systematic error of about 10 MeV [9].

At well above the threshold, the forward-backward asymmetry of the top quark with respect to the incoming electron beam becomes highly sensitive to the polarization of the Z in the intermediate state. Using the anticipated capability of the ILC to polarize the incoming beams, one could separately extract the right-handed and left-handed top coupling to Z. Fig. 4 shows the deviation from the Standard Model for the right-handed and left-handed couplings for a variety of models [4]. It also shows the 68% confidence level ellipses for the ILC and LHC measurements. With the anticipated sensitivity of the ILC, one could effectively distinguish many new physics models.

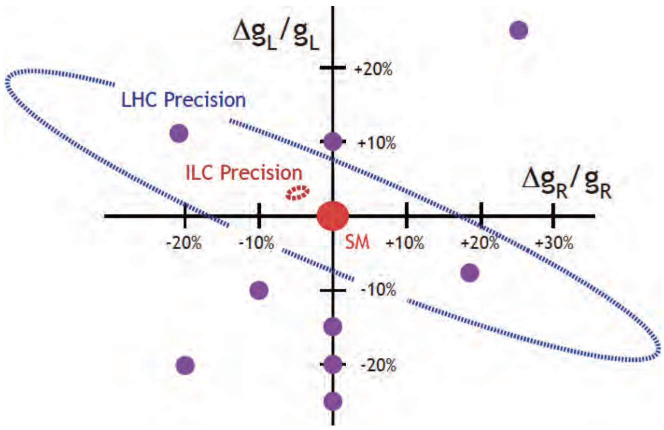

Fig. 4: Deviation of top-Z couplings from the Standard Model shown separately for right-handed and left-handed couplings. Points for various models of new physics are also shown.

Higgs Factory

Recently, the ILC community proposed that the ILC project should be started as a Higgs factory in its first stage. The idea is to take 2000 fb^{-1} of data at CM energy of 250 GeV. It would take about 10 years of running time. Consequently, it is natural to ask how this compares to the case where one starts with a 500 GeV capability.

Fig. 5 shows the Higgs coupling accuracies by the Higgs factory compared to the case where 1000 fzb^{-1} each of data is taken at 500 GeV and at 250 GeV. There the effective field theory approach is used and it is assumed that LHC data of 3000 fb^{-1} is available. They are seen to be roughly equivalent.

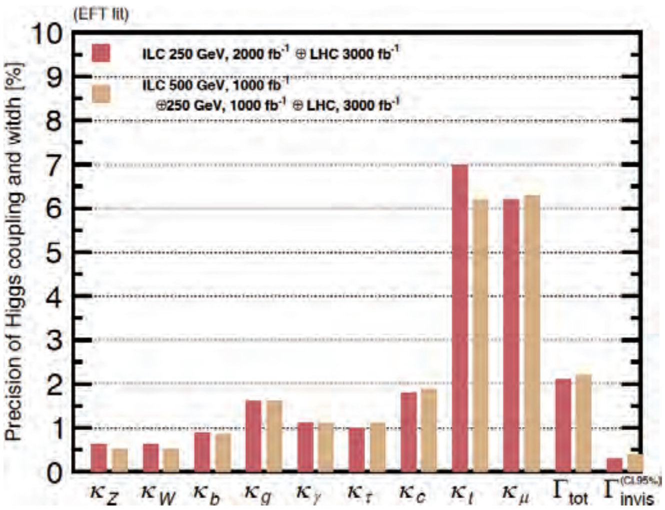

Fig. 5: Accuracies of Higgs coupling measurements at the Higgs factory is compared to a situation where the same total amount of data is taken at 500 GeV and at 250 GeV.

PRESENT STATUS AND FUTURE PLANS

Following the discovery of the Higgs boson and the completion of the ILC technical design report, the Japanese government established the ILC advisory panel to evaluate the ILC's scientific merits, technical maturity, the availability of human resources, and issues of governance and management.

In December 2016, the ILC community proposed the construction of a Higgs factory as the first stage of the ILC. Together with recent progress in superconducting acceleration technology, this would indicate a cost reduction of up to 40%. The proposal is to be formally endorsed by the International Committee for Future Accelerators (ICFA) in November, 2017.

The ILC advisory panel is now in the final phase of the evaluation. Once the endorsement by ICFA is in place, the final report is expected to come within several months.

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Hitoshi Yamamoto is a professor of physics at Tohoku University. He received his PhD at the California Institute of Technology. He was a senior research fellow at the Enrico Fermi Institute before joining Harvard University as a junior faculty member. After becoming a professor at the University of Hawaii he then went to Tohoku University and became a professor. Currently, he is involved in the KEK B-factory and the International Linear Collider (ILC). He served as the associate director for physics and the detector of the Linear Collider Collaboration (LCC) from 2012 to 2017.