ILC Higgs Physics Potential

Shin-ichi Kawada (KEK)
on behalf of ILC IDT WG3
(ILC International Development Team)

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Why We Need Precision on Higgs?

• Until today: SM-like Higgs boson and no new physics
• But we know there are missing elements such as nature of dark matter, matter-antimatter asymmetry, neutrino mass, origin of EW symmetry breaking, etc, that cannot be explained by SM. Thus, we need new physics.

• Discovered Higgs boson is a window to new physics.
• Many new physics models predict small deviation from the SM (a few to 10%) ---> O(1%) level precision is necessary
The **International Linear Collider (ILC)**

- $e^+e^-$ collider, $\sqrt{s} = 250$ GeV (upgradable to 500 GeV, 1 TeV)
- polarized beam ($e^-: \mp 80\%, e^+: \pm 30\%$)
- clean environment, known initial state
- matured technology, TDR published

2000 fb$^{-1}$ @ 250 GeV
200 fb$^{-1}$ @ 350 GeV
4000 fb$^{-1}$ @ 500 GeV

under in-depth consideration by the Japanese government

ILC IDT WG3 (Physics & Detectors) webpage is [here](#).
Higgs Production at the ILC

\( \sqrt{s} = 250 \text{ GeV} \)
Higgs-strahlung (Zh) dominant
maximum cross section around 250 GeV
---\( \Rightarrow \) Higgs factory, O(1M) Higgs events

\( \sqrt{s} = 500 \text{ GeV} \)
WW-fusion dominant
improve many couplings
access to Top-Yukawa, Higgs self-coupling
Key Point: Model Independence

- LHC: all measurements are $\sigma \times \text{BR}$
- ILC: $\sigma \times \text{BR}$ measurements + $\sigma$ measurement
Key Measurement: $\sigma_{Zh}$

**Unique measurement at lepton colliders**

\[
M_X^2 = \left( p_{CM} - (p_{\mu^+} + p_{\mu^-}) \right)^2
\]

- well-defined initial states
- without looking into Higgs (recoil mass technique)

**ILC250, 2 ab^{-1}**

$\Delta m_h = 14$ MeV, $\frac{\Delta \sigma_{Zh}}{\sigma_{Zh}} = 0.7\%$
Direct Higgs Observables at ILC250

\( \sigma_{Zh} \times \text{BR}(h \rightarrow bb) \)

\( \sigma_{vvh} \times \text{BR}(h \rightarrow bb) \)

\( \sigma_{Zh} \times \text{BR}(h \rightarrow cc) \)

\( \sigma_{Zh} \times \text{BR}(h \rightarrow gg) \)

\( \sigma_{Zh} \times \text{BR}(h \rightarrow WW^*) \)

\( \sigma_{Zh} \times \text{BR}(h \rightarrow ZZ^*) \)

\( \sigma_{Zh} \times \text{BR}(h \rightarrow \tau\tau) \)

\( \sigma_{Zh} \times \text{BR}(h \rightarrow \gamma\gamma) \)

\( \sigma_{Zh} \times \text{BR}(h \rightarrow \mu\mu) \)

\( \sigma_{Zh} \times \text{BR}(h \rightarrow \text{invisible}) \)

+ differential cross section

\( \circ \): speciality of \( e^+e^- \) colliders

b- and c-likeliness for \( h \rightarrow b\bar{b}, c\bar{c}, gg, \) and other

Combined Higgs BR in next-next talk
Example: Flavor Tagging

Performance of flavor tagging is essential for $h \to b\bar{b}$, $h \to c\bar{c}$, and $h \to gg$ study.

Recent study: s-jet tagging for SM $h \to ss$ and BSM $h \to c\bar{c}/\bar{c}s$ study. The first study report can be found [here](#).
Higgs Coupling Determination in SMEFT Formalism

\[ \Delta \mathcal{L} = \frac{c_H}{2v^2} \partial^\mu (\Phi^\dagger \Phi) \partial_{\mu} (\Phi^\dagger \Phi) + \frac{c_T}{2v^2} (\Phi^\dagger \overleftrightarrow{D^\mu} \Phi) (\Phi^\dagger \overleftrightarrow{D^\mu} \Phi) - \frac{c_6}{v^2} (\Phi^\dagger \Phi)^3 \]

\[ + \frac{g^2 c_{WW}}{m_W^2} \Phi^\dagger \Phi W^a_{\mu \nu} W^a_{\mu \nu} + \frac{4g g' c_{WB}}{m_W^2} \Phi^\dagger t^a \Phi W^a_{\mu \nu} B_{\mu \nu} \]

\[ + \frac{g^2 c_{BB}}{m_W^2} \Phi^\dagger B_{\mu \nu} B_{\mu \nu} + \frac{g^3 c_{3W}}{m_W^2} \epsilon_{abc} W^a_{\mu \nu} W_{\rho \nu}^b W_{c \rho}^c \]

\[ + \frac{i c_{CHL}}{v^2} (\Phi^\dagger \overleftrightarrow{D^\mu} \Phi) (\overline{L} \gamma_{\mu} L) + 4i \frac{c'_{CHL}}{v^2} (\Phi^\dagger t^a \overleftrightarrow{D^\mu} \Phi) (\overline{L} \gamma_{\mu} t^a L) \]

\[ + \frac{i c_{CHE}}{v^2} (\Phi^\dagger \overleftrightarrow{D^\mu} \Phi) (\overline{e} \gamma_{\mu} e) \]

10 EFT operators \( (h, W, Z, \gamma) \): \( c_H, c_T, c_6, c_{WW}, c_{WB}, c_{BB}, c_{3W}, c_{HL}, c'_{HL}, c_{HE} \)

5 EFT operators modifying \( h \) couplings to \( b, c, \tau, \mu, g \)

2 EFT operators for contact interaction with quarks

4 SM parameters: \( g, g', v, \lambda \)

2 parameters for \( h \to \) invisible and exotics

"Warsaw" basis
- gauge invariant
- Lorentz invariant
- CP conserving
- 23 parameters
Observables in SMEFT

• In total: 39 observables
  • Electroweak Precision Observables (9)
  • Triple Gauge Coupling observables (3)
  • Higgs observables from LHC and ILC (3 + 12 × 2)
    • LHC: $BR(h \rightarrow \gamma\gamma, \gamma Z, ZZ^*)$
    • ILC: multiplied by 2 because of beam polarization

• Systematics are considered in the global fit

• At the ILC, it is possible to determine all the 23 parameters simultaneously.
~1% or better precisions can be reached at ILC250 in a highly model-independent way.

More improvements and new results with ILC500.

S1*: based on current results
S2*: assume improvements in jet clustering, flavor tagging, etc.
(see backup for details)
There are no drastic difference between precision with $2 \text{ ab}^{-1}$, polarized beam and precision with $5 \text{ ab}^{-1}$, unpolarized beam at 250 GeV.

The polarization is very powerful, essentially compensating the advantage of large data set.
Comparison with HL-LHC Higgs Capabilities

Not simple comparison due to different framework.
----> add assumptions in EFT fit
(model-dependent fit)
(1) no BSM decay of Higgs
(2) no anomalous couplings in $hWW$ and $hZZ$

Great improvement at the ILC in many channels.
Nice synergy with HL-LHC, typically in rare channel.
Higgs Self-coupling

Direct probe of Higgs potential

\[ \Delta \lambda_{hhH}/\lambda_{hhH} \]

<table>
<thead>
<tr>
<th></th>
<th>[ \Delta \lambda_{hhH}/\lambda_{hhH} ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 ab(^{-1}) at ILC500</td>
<td>27%</td>
</tr>
<tr>
<td>+8 ab(^{-1}) at ILC1000</td>
<td>10%</td>
</tr>
</tbody>
</table>

More improvements are expected:
- b-tagging
- jet reconstruction
- kinematic fitting
- ...

see poster by Yasser Radkhorrami (DESY) about kinematic fitting
Higgs Self-coupling: What Happens If $\lambda_{hhh} \neq \lambda_{SM}$

- $\lambda_{hhh}$ can be significantly enhanced in BSM such as EW baryogenesis models.
- Complementarity in $Zhh/\nu\bar{\nu}hh$ (and LHC): interferences different
- If $\lambda_{hhh}/\lambda_{SM} = 2$, $\Delta\lambda_{hhh}/\lambda_{hhh} \sim 15\%$ at ILC500 with $Zhh$
Summary

• Precision measurement on Higgs is a window to new physics.
• Precise and highly model-independent measurements of Higgs boson are possible at the ILC under EFT framework.
• Many couplings can be reached ~1% precision at ILC250.
• Beam polarization is very powerful, essentially compensating $\times 2.5$ luminosity.
• At ILC500 and above, top-Yukawa and Higgs self-coupling can be measured.
BACKUP
Processes toward Realization of ILC

**Government Level**
- **2018.12**: Announcement by Japanese government
- **2019.3**: Discussion among governments
  - Exchange of information
- **2020.5**: Strengthen US-Japan Discussion Group, cost reduction R&D, governance discussion
- **2024-**: Agreement on governance, operation, sharing of cost and human resources

**Physicists Level**
- **2018.12**: SCJ Master Plan
- **2019.3**: SCJ by MEXT
- **2020.5**: EPPSU submitted to CERN

**2019.3**
- **3/7**: LCB/ICFA mtgs. @ Tokyo

**2020.5**
- **Next Roadmap by MEXT**
- **Oct. 2019**: MOU among research labs on start of the preparation phase under approval by each government

**2024-**
- **ILC pre-lab** (4 years)

**Critical decision process**

**Processes toward Realization of ILC**

- **Draft proposal by researchers on international cost sharing**
- **Establish KEK International WG**
  - Produce draft for international sharing of human and material resources
  - Talks with other countries

Good enough design for the final approval of construction, resolution of remaining technical issues

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*ICFA*: international organization of researchers consisting of directors of world’s major accelerator labs and representatives of researchers.

*ILC pre-lab*: International research organization for the preparation of ILC based on agreements among world’s major accelerator labs such as KEK, CERN, FNAL, DESY etc.
Example of Deviation From SM
ILC Running Scenario

optimized scenario with considering Higgs/Top/New physics

~20 years running with energy range [250-500] GeV, beam polarization sharing

2000 fb\(^{-1}\) @ 250 GeV
200 fb\(^{-1}\) @ 350 GeV
4000 fb\(^{-1}\) @ 500 GeV
(iii.2.7) Top-Yukawa coupling

- largest Yukawa coupling; crucial role
- non-relativistic tt-bar bound state correction: enhancement by ≈2 at 500 GeV
- Higgs CP measurement

![Graph showing the cross-section (σ) as a function of √s (GeV) for various processes like ttH (w/NRQCD), ttZ (w/NRQCD), ttg (g- bb), and ttH (w/o NRQCD).]

<table>
<thead>
<tr>
<th>Δg_{ttH}/g_{ttH}</th>
<th>500 GeV</th>
<th>+1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snowmass</td>
<td>7.8%</td>
<td>2.0%</td>
</tr>
<tr>
<td>H20</td>
<td>6.3%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

### GigaZ – Basic facts

<table>
<thead>
<tr>
<th>arXiv:1506.07830</th>
<th>$\text{sgn}(P(e^-), P(e^+)) =$</th>
<th>sum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(-,+)</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>(+,-)</td>
<td>10</td>
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<td></td>
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<td>10</td>
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<tr>
<td></td>
<td>(+,+),</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Luminosity [fb$^{-1}$]</th>
<th>40</th>
<th>40</th>
<th>10</th>
<th>10</th>
<th>\text{sum}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(P_{e^-}, P_{e^+})$ [nb]</td>
<td>83.5</td>
<td>63.7</td>
<td>50.0</td>
<td>40.6</td>
<td>\text{sum}</td>
</tr>
<tr>
<td>$Z$ events [$10^9$]</td>
<td>2.4</td>
<td>1.8</td>
<td>0.36</td>
<td>0.29</td>
<td>4.9</td>
</tr>
<tr>
<td>Hadronic $Z$ events [$10^9$]</td>
<td>1.7</td>
<td>1.3</td>
<td>0.25</td>
<td>0.21</td>
<td>3.4</td>
</tr>
</tbody>
</table>

=230xLEP, 8500xSLC

- Accelerator scenario 3.7Hz@M$_Z$/2 + 3.7 Hz@125 GeV to produce positrons
- With 2625 bunches an instantaneous luminosity of $5 \times 10^{33}$ cm$^{-2}$s$^{-1}$ $\Rightarrow$ 100 fb$^{-1}$ in 1.3 years after lumi upgrade
- More possible by improved damping rings and BDS system
The ILD Concept

From key requirements from physics:

- **p_t resolution** (total ZH x-section)
  \[ \sigma(1/p_t) = 2 \times 10^{-5} \text{ GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2} \theta) \]

- **vertexing** \( (H \rightarrow bb/cc/\tau) \)
  \[ \sigma(d_0) < 5 \oplus 10 / (p[\text{GeV}] \sin^{3/2} \theta) \mu\text{m} \]

- **jet energy resolution** 3-4%
  \( (H \rightarrow \text{invisible}) \)

- **hermeticity** \( \theta_{\text{min}} = 5 \text{ mrad} \)
  \( (H \rightarrow \text{invis, BSM}) \)

To key features of the detector:

- **low mass tracker**:
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer
  - **high granularity calorimeters** optimised for particle flow

\[ \approx \text{CMS} / 4 \]
\[ \approx \text{ATLAS} / 2 \]
\[ \approx \text{ATLAS} / 3 \]

Not fully fair comparison - since experimental environment at ILC very different:

- much lower backgrounds
- much less radiation
- much lower collision rate
- ...

\[ \approx \text{CMS} / 40 \]
SiD Overview

- Compact design in a 5 T field
- Robust all-silicon tracking with excellent momentum resolution
- Time-stamping for single bunch crossings
- Highly granular calorimetry optimized for Particle Flow
- Integrated design: All parts work in tandem
- Iron flux return / muon identifier is part of SiD self-shielding

A compact, cost-constrained detector designed to make precision measurements and be sensitive to a wide range of new phenomena
Observables To Couplings: $\kappa$-formalism (1)

(1) recoil mass technique ---> $\sigma_{Zh}$
(2) $\sigma_{Zh}$ ---> $\kappa_Z$ ---> $\Gamma(h \rightarrow ZZ^*)$
(3) $WW$-fusion measurement ---> $\kappa_W$ ---> $\Gamma(h \rightarrow WW^*)$
(4) total width $\Gamma_h = \frac{\Gamma(h \rightarrow ZZ^*)}{BR(h \rightarrow ZZ^*)}$, or $\Gamma_h = \frac{\Gamma(h \rightarrow WW^*)}{BR(h \rightarrow WW^*)}$
(5) then all other couplings $\Gamma_h \times BR(h \rightarrow XX) ---> \kappa_X$

Simple, but **model-dependent** anomalous coupling is not considered.
Observables To Couplings: $\kappa$-formalism (2)

Assume $\zeta_Z = 0$ in $\kappa$-formalism: model-dependent

$$\delta \mathcal{L} = \frac{m_Z^2}{v} (1 + \eta_Z) h Z_\mu Z^\mu + \frac{1}{2v} \zeta_Z h Z_{\mu \nu} Z^{\mu \nu}$$

\[ \begin{align*}
\sigma(e^+e^- \to Zh)_{SM} &= 1 + 2\eta_Z + 5.7\zeta_Z \\
\Gamma(h \to ZZ^*)_{SM} &= 1 + 2\eta_Z - 0.5\zeta_Z
\end{align*} \]
Synergy with HL-LHC

LHC meas.: $\text{BR}(h \rightarrow \gamma\gamma)/\text{BR}(h \rightarrow ZZ^*)$, $\text{BR}(h \rightarrow \gamma Z)/\text{BR}(h \rightarrow ZZ^*)$

\[
\delta \Gamma(h \rightarrow \gamma\gamma) = 528 \delta Z_A - c_H + \ldots
\]

\[
\delta \Gamma(h \rightarrow Z\gamma) = 290 \delta Z_{AZ} - c_H + \ldots
\]

\[
\delta \Gamma(h \rightarrow ZZ^*) = -0.50 \delta Z_Z - c_H + \ldots
\]

*loop induced $h \rightarrow \gamma\gamma/\gamma Z$ provide two very strong constraints*
Systematic Errors

• 0.1% from theory computations
• 0.1% from luminosity
• 0.1% from beam polarizations
• 0.1% + 0.3%/sqrt(L/250) from b-tagging and analysis
S2 Assumption

• 10% improvement in signal efficiency of the jet clustering algorithm

• 20% improvement in the performance of the flavor tagging algorithm

• 20% improvement in statistics by including more signal channels in $\sigma_{zh} \times BR(h \rightarrow WW^*)$

• a factor of 10 improvement in the precision electroweak input $A_{LR}$ through the measurement of $e^+e^- \rightarrow \gamma Z$ with polarized beams at ILC250

• 30% improvement in the precision of Higgs self-coupling and top Yukawa coupling at ILC500
Power of TGC

Impact of improved TGC precisions

- HL-LHC ⊕ ILC250
- HL-LHC ⊕ ILC250, TGCs from LEP

× 1/3
× 1/2

Precision of Higgs boson couplings [%]

Z, W, b, τ, g, c, Γ_{inv}, Γ_h, γ, Zγ, μ