Physics Potential at the ILC

Keisuke Fujii (KEK)

arXiv: 1310.0763 (Higgs)
arXiv: 1307.5248 (BSM)
arXiv: 1307.8265 (Top)
arXiv: 1307.3962 (EW)
• Success of the SM = success of gauge principle
  \( W_T \) and \( Z_T \) = gauge fields of the EW gauge symmetry

• Gauge symmetry forbids explicit mass terms for \( W \) and \( Z \)
  \( \rightarrow \) it must be broken by something condensed in the vacuum:
  \( \langle 0 | I_3, Y | 0 \rangle \neq 0 \quad \langle 0 | I_3 + Y | 0 \rangle = 0 \)

• This “something” supplies 3 longitudinal modes of \( W \) and \( Z \):
  \( W_L^+, W_L^-, Z_L \) : Goldstone modes

• Left- (\( f_L \)) and right-handed (\( f_R \)) matter fermions carry different EW charges.
  Their explicit mass terms also forbidden by the EW gauge symmetry
  They must be generated through their Yukawa interactions with some weak-charged vacuum

• In the SM, the same “something” mixes \( f_L \) and \( f_R \) \( \rightarrow \) generating masses and inducing flavor-mixings

• In order to form the Yukawa interaction terms, we need a complex doublet scalar field, which has four
  real components. The SM identifies three of them with the Goldstone modes.

• We need one more to form a complex doublet, which is the physical Higgs boson.

• This SM symmetry breaking sector is the simplest and the most economical, but there is no reason for it.
  The symmetry breaking sector might be more complex.

• We don’t know whether the “something” is elementary or composite.
• We don’t know why and how it condensed in the vacuum.

• We knew it’s there in the vacuum with a vev of 246 GeV and a custodial SU(2) (\( \rho = 1 \)). But other than that
  we didn’t know almost anything about the “something” \( \text{until July 4, 2012.} \)
Since the July 4th, the world has changed!
The discovery of the ~125 GeV boson at LHC could be called a quantum jump.

- $X(125) \rightarrow \gamma\gamma$ means $X$ is a neutral boson and $J \neq 1$ (Landau-Yang theorem).
  Recent LHC results strongly suggest $J^P=0^+$.  
- $X(125) \rightarrow ZZ^*, \; WW^* \Rightarrow \exists XVV$ couplings: ($V=W/Z$: gauge bosons)
- There is, however, no gauge coupling like XVV, only XXVV or XXV
  $\Rightarrow$ XVV probably from XXVV with one $X$ replaced by $\langle X \rangle \neq 0$, namely $\langle X \rangle XVV$
  $\Rightarrow$ There must be $\langle X \rangle \langle X \rangle VV$, a mass term for $V$.
  $\Rightarrow$ $X$ is at least part of the origin of the masses of $V=W/Z$.
  $\Rightarrow$ This is a great step forward but we need to know whether $\langle X \rangle$ saturates
  the SM vev = 246GeV. We need to know WHY $X$ condensed in the vacuum.
- $X \rightarrow ZZ^*$ means, $X$ can be produced via $e^+e^- \rightarrow Z^* \rightarrow ZX$.
  ![Diagram](image)
- By the same token,
  $X \rightarrow WW^*$ means, $X$ can be produced via $W$ fusion: $e^+e^- \rightarrow \nu\nu X$.
- So we now know that the major Higgs production mechanisms in $e^+e^-$
collisions are indeed available at the ILC $\Rightarrow$ No lose theorem for the ILC.
- ~125GeV is the best place for the ILC, where variety of decay modes are
  accessible.
- We need to check this ~125GeV boson in detail to see if it has indeed all the
  required properties of the something in the vacuum.
What Properties to Measure?

The Key is the Mass-Coupling Relation

- Properties to measure are
  - mass, width, $J^{PC}$
  - Gauge couplings
  - Yukawa couplings
  - Self-coupling

- The key is to measure the mass-coupling relation

If the 125GeV boson is the one to give masses to all the SM particles, coupling should be proportional to mass.

Any deviation from the straight line signals BSM!

The Higgs is a window to BSM physics!
Our Mission = Bottom-up Model-Independent Reconstruction of the EWSB Sector through Precision Higgs Measurements

- Multiplet structure:
  - Additional singlet? \((\phi + S)\)
  - Additional doublet? \((\phi + \phi')\)
  - Additional triplet? \((\phi + \Delta)\)

- Underlying dynamics:
  - Why did the Higgs condense?
  - Weakly interacting or strongly interacting? = elementary or composite?

- Relations to other questions of HEP:
  - \(\phi + S\) \(\rightarrow\) (B-L) gauge, DM, ...
  - \(\phi + \phi'\) \(\rightarrow\) Type I: \(m_\nu\) from small vev, ...
  - \(\phi + \Delta\) \(\rightarrow\) Type X: \(m_\nu\) (rad.seesaw), ...
  - \(\lambda > \lambda_{SM}\) \(\rightarrow\) EW baryogenesis?
  - \(\lambda \downarrow 0\) \(\rightarrow\) inflation?

There are many possibilities!

Different models predict different deviation patterns --> Fingerprinting!

<table>
<thead>
<tr>
<th>Model</th>
<th>(\mu)</th>
<th>(\tau)</th>
<th>(b)</th>
<th>(c)</th>
<th>(t)</th>
<th>(g_\nu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet mixing</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
</tr>
<tr>
<td>2HDM-I</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
</tr>
<tr>
<td>2HDM-II (SUSY)</td>
<td>\uparrow</td>
<td>\uparrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
</tr>
<tr>
<td>2HDM-X (Lepton-specific)</td>
<td>\uparrow</td>
<td>\uparrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
</tr>
<tr>
<td>2HDM-Y (Flipped)</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
<td>\downarrow</td>
</tr>
</tbody>
</table>

Mixing with singlet

\[
\frac{g_{hVV}}{g_{h_{SM}VV}} = \frac{g_{hf\bar{f}}}{g_{h_{SM}f\bar{f}}} = \cos \theta \simeq 1 - \frac{\delta^2}{2}
\]

Composite Higgs

\[
\begin{align*}
\frac{g_{hVV}}{g_{h_{SM}VV}} & \simeq 1 - 3%(1\text{ TeV/f})^2 \\
\frac{g_{hf\bar{f}}}{g_{h_{SM}f\bar{f}}} & \simeq 1 - 9%(1\text{ TeV/f})^2
\end{align*}
\]

SUSY

\[
\frac{g_{hh\bar{b}b}}{g_{h_{SM}h_{SM}\bar{b}b}} \simeq 1 + 1.7\% \left(\frac{1\text{ TeV}}{m_A}\right)^2
\]

Expected deviations are small --> Precision!

For the precision we need a 500GeV LC
Why 250-500 GeV?

Three well known thresholds

**ZH @ 250 GeV (~M_z+M_H+20 GeV):**
- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measurement of HZZ coupling (recoil mass) \( \rightarrow \) couplings to H (other than top)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, \( \gamma \) (loop)

**ttbar @ 340-350 GeV (~2mt):** ZH meas. Is also possible
- Threshold scan \( \rightarrow \) theoretically clean mt measurement: \( \Delta m_t(M_S) \approx 100 \text{ MeV} \)
  \( \rightarrow \) test stability of the SM vacuum
  \( \rightarrow \) indirect meas. of top Yukawa coupling
- \( A_{FB} \), Top momentum measurements
- Form factor measurements \( \gamma \gamma \rightarrow HH @ 350 \text{GeV} \) possibility

**vvH @ 350 - 500 GeV:**
- HWW coupling \( \rightarrow \) total width \( \rightarrow \) absolute normalization of Higgs couplings

**ZHH @ 500 GeV (~M_z+2M_H+170 GeV):**
- Prod. cross section attains its maximum at around 500 GeV \( \rightarrow \) Higgs self-coupling

**ttbarH @ 500 GeV (~2mt+M_H+30 GeV):**
- Prod. cross section becomes maximum at around 800 GeV.
- QCD threshold correction enhances the cross section \( \rightarrow \) top Yukawa measurable at 500 GeV concurrently with the self-coupling

We can complete the mass-coupling plot at ~500 GeV!
ILC 250
Recoil Mass Measurement
The flagship measurement of ILC 250

Recoil Mass

![Graph showing recoil mass distribution with key points](image)

**Key Point:**
Model-independent absolute measurement of $\sigma_{ZH}$ (the HZZ coupling)

- **$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$**
  - Invisible decay detectable!

- **$250 \text{ fb}^{-1} @ 250 \text{ GeV}$**
  - $m_H = 125 \text{ GeV}$
  - $\Delta \sigma_H / \sigma_H = 2.6\%$
  - $\Delta m_H = 30 \text{ MeV}$
  - $BR(\text{invisible}) < 1\% @ 95\% \text{ C.L.}$

Scaled from $m_H = 120 \text{ GeV}$

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K.Fujii, Pheno2014, Pittsburgh, May 7, 2014
By template fitting, we can separate $H \rightarrow bb$, $cc$, $gg$, others!

What we measure is not BR itself but $\sigma \times BR$.

To extract BR from $\sigma \times BR$, we need $\sigma$ from the recoil mass measurement.

$$BR = \frac{\sigma \times BR}{\sigma}$$

$\Delta\sigma/\sigma = 2.6\%$ eventually limits the BR measurements.

$\Delta\sigma BR/\sigma BR$

<table>
<thead>
<tr>
<th>process</th>
<th>@250GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZH</td>
<td></td>
</tr>
<tr>
<td>Int. Lumi. [fb]</td>
<td>250</td>
</tr>
<tr>
<td>$\Delta\sigma/\sigma$</td>
<td>2.6%</td>
</tr>
<tr>
<td>decay mode</td>
<td>$\Delta\sigma BR/\sigma BR$</td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>1.2%</td>
</tr>
<tr>
<td>$H \rightarrow cc$</td>
<td>8.3%</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>7%</td>
</tr>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>6.4%</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>4.2%</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>18%</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>34%</td>
</tr>
</tbody>
</table>

preliminarily

K.Fujii, Pheno2014, Pittsburgh, May 7, 2014
From BRs to Couplings
One of the major advantages of the LC

To extract couplings from BRs, **we need the total width** in general:

\[ g_{HAA}^2 \propto \Gamma(H \rightarrow AA) = \Gamma_H \cdot BR(H \rightarrow AA) \]

To determine the total width, we need at least one partial width and corresponding BR:

\[ \Gamma_H = \frac{\Gamma(H \rightarrow AA)}{BR(H \rightarrow AA)} \]

In principle, we can use A=Z, or W for which we can measure both the BRs and the couplings:

**BR=O(1%)**: precision limited by low stat.
for H→ZZ* events

250 fb^{-1}@250 GeV
\[ \Delta \Gamma_H / \Gamma_H \approx 20\% \]

More advantageous but not easy at low E

250 fb^{-1}@250 GeV
\[ \Delta \Gamma_H / \Gamma_H \approx 11\% \]
ILC 500
Width and BR Measurements at 500 GeV
Addition of 500GeV data to 250GeV data

<table>
<thead>
<tr>
<th>E</th>
<th>independent measurements</th>
<th>relative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>$\sigma_{ZH}$</td>
<td>2.6%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{ZH} \cdot Br(H \rightarrow bb)$</td>
<td>1.2%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{ZH} \cdot Br(H \rightarrow cc)$</td>
<td>8.3%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{ZH} \cdot Br(H \rightarrow gg)$</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{ZH} \cdot Br(H \rightarrow WW^*)$</td>
<td>6.4%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{ZH} \cdot Br(H \rightarrow \tau^+\tau^-)$</td>
<td>4.2%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\nu\bar{\nu}H} \cdot Br(H \rightarrow bb)$</td>
<td>10.5%</td>
</tr>
<tr>
<td>500</td>
<td>$\sigma_{ZH}$</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{ZH} \cdot Br(H \rightarrow bb)$</td>
<td>1.8%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{ZH} \cdot Br(H \rightarrow cc)$</td>
<td>13%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{ZH} \cdot Br(H \rightarrow gg)$</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{ZH} \cdot Br(H \rightarrow WW^*)$</td>
<td>9.2%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{ZH} \cdot Br(H \rightarrow \tau^+\tau^-)$</td>
<td>5.4%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\nu\bar{\nu}H} \cdot Br(H \rightarrow bb)$</td>
<td>0.66%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\nu\bar{\nu}H} \cdot Br(H \rightarrow cc)$</td>
<td>6.2%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\nu\bar{\nu}H} \cdot Br(H \rightarrow gg)$</td>
<td>4.1%</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\nu\bar{\nu}H} \cdot Br(H \rightarrow WW^*)$</td>
<td>2.4%</td>
</tr>
</tbody>
</table>

The numbers in the parentheses are as of 250 fb$^{-1}$ @250 GeV

ILD DBD Full Simulation Study

$250 \text{ fb}^{-1}@250 \text{ GeV}$
$+500 \text{ fb}^{-1}@500 \text{ GeV}$

$m_H = 125 \text{ GeV}$
Top Yukawa Coupling
At 500 GeV we can directly access the top Yukawa coupling!

Cross section maximum at around
\( E_{cm} = 800 \text{GeV} \)

- Philipp Roloff, LCWS12
- Tony Price, LCWS12

DBD Full Simulation

\[
\Delta g_Y(t) / g_Y(t) = 9.9\%
\]

Tony Price, LCWS12

Notice \( \sigma(500+20\text{GeV})/\sigma(500\text{GeV}) \sim 2 \)

Moving up a little bit helps significantly!
And then Higgs Self-coupling
the force that made the Higgs condense in the vacuum

\[ V(\Phi) \]

\[ \phi^0 \]

\[ \phi^+ \]

We need to measure the Higgs self-coupling

\[ = \text{We need to measure the shape of the Higgs potential} \]

The measurement is very difficult even at ILC.
The Problem: BG diagrams dilute self-coupling contribution

\[ \sigma = \lambda^2 S + \lambda I + B \]

\[ \frac{\Delta \lambda}{\lambda} = F \cdot \frac{\Delta \sigma}{\sigma} \]

F = 0.5 if no BG diagrams

\[ \frac{\Delta \lambda}{\lambda} = 1.80 \frac{\Delta \sigma}{\sigma} \]

\[ \frac{\Delta \lambda}{\lambda} = 1.66 \frac{\Delta \sigma}{\sigma} \]

\[ \frac{\Delta \lambda}{\lambda} = 0.85 \frac{\Delta \sigma}{\sigma} \]

\[ \frac{\Delta \lambda}{\lambda} = 0.76 \frac{\Delta \sigma}{\sigma} \]
Higgs self-coupling @ 500 GeV

\[ e^+ + e^- \rightarrow ZHH \]

\[ M(H) = 120 \text{GeV} \quad \int Ldt = 2ab^{-1} \]

\[ P(e^-, e^+) = (-0.8, +0.3) \]

### Energy (GeV)

<table>
<thead>
<tr>
<th>Modes</th>
<th>signal</th>
<th>background (tt, ZZ, ZZH/ZZZ)</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>500</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZHH ( \rightarrow (l\bar{l})(b\bar{b})(b\bar{b}) )</td>
<td>3.7</td>
<td>4.3</td>
<td>1.5σ</td>
</tr>
<tr>
<td>ZHH ( \rightarrow (\nu\bar{\nu})(b\bar{b})(b\bar{b}) )</td>
<td>4.5</td>
<td>6</td>
<td>1.5σ</td>
</tr>
<tr>
<td>ZHH ( \rightarrow (q\bar{q})(b\bar{b})(b\bar{b}) )</td>
<td>8.5</td>
<td>7.9</td>
<td>2.5σ</td>
</tr>
<tr>
<td>ZHH ( \rightarrow (q\bar{q})(b\bar{b})(b\bar{b}) )</td>
<td>13.6</td>
<td>30.7</td>
<td>2.2σ</td>
</tr>
<tr>
<td>ZHH ( \rightarrow (q\bar{q})(b\bar{b})(b\bar{b}) )</td>
<td>18.8</td>
<td>90.6</td>
<td>1.9σ</td>
</tr>
</tbody>
</table>

**Hypothesis test**

\[ \chi^2 \text{ as a function of cross section} \]

\[ \frac{\delta \sigma}{\sigma} = 27\% \]

\[ \frac{\delta \lambda}{\lambda} = 44\% \]

(ZHH excess significance: 5.0σ)

(c.f. 80% for qqbbbb at the LoI time)
\[ e^+ + e^- \rightarrow \nu\bar{\nu}HH \]

\[ M(H) = 120 \text{GeV} \quad \int L dt = 2 \text{ab}^{-1} \]

\[ P(e^-, e^+) = (-0.8, +0.2) \]

<table>
<thead>
<tr>
<th></th>
<th>Expected</th>
<th>After Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu\nu hh ) (WW-F)</td>
<td>272</td>
<td>35.7</td>
</tr>
<tr>
<td>( \nu\nu hh ) (ZHH)</td>
<td>74</td>
<td>3.88</td>
</tr>
<tr>
<td>( \text{BG (tt/} \nu\nu ZH) )</td>
<td>(7.86 \times 10^3)</td>
<td>33.7</td>
</tr>
<tr>
<td>significance</td>
<td>0.3</td>
<td>4.29</td>
</tr>
</tbody>
</table>

- better sensitivity factor
- benefit more from beam polarization
- \( \text{BG tt x-section smaller} \)
- more boosted b-jets

\[ \frac{\Delta\sigma}{\sigma} \approx 23\% \]

\[ \frac{\Delta\lambda}{\lambda} \approx 18\% \]

Double Higgs excess significance: \( > 7\sigma \)

Higgs self-coupling significance: \( > 5\sigma \)

ILD DBD Study (Junping Tian)
HHH Prospects

Scaled to M(H)=125GeV

Scenario A: HH→bbbb, full simulation done
Scenario B: by adding HH→bbWW*, full simulation ongoing,
  expect ~20% relative improvement
Scenario C: color-singlet clustering, future improvement,
  expected ~20% relative improvement (conservative)

<table>
<thead>
<tr>
<th></th>
<th>HHH</th>
<th>500 GeV</th>
<th></th>
<th>500 GeV + 1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td>Baseline</td>
<td>104%</td>
<td>83%</td>
<td>66%</td>
<td>26%</td>
</tr>
<tr>
<td>LumiUP</td>
<td>58%</td>
<td>46%</td>
<td>37%</td>
<td>16%</td>
</tr>
</tbody>
</table>

Baseline
250 GeV: 250 fb⁻¹
500 GeV: 500 fb⁻¹
1 TeV: 1000 fb⁻¹

LumiUP
250 GeV: 1150 fb⁻¹
500 GeV: 1600 fb⁻¹
1 TeV: 2500 fb⁻¹

ILD DBD Study
(Junping Tian, Masakazu Kurata)
Top Yukawa Coupling at 1TeV
Now it is fully open!

Cross section maximum at around
Ecm = 800GeV

Tony Price & Tomohiko Tanabe: ILD DBD Study
Philipp Roloff & Jan Strube: SiD DBD Study

DBD Full Simulation

Similar significance in both modes
8-jet mode: 7.9σ (TMVA)
L+6-jet mode: 8.4σ (TMVA)

1 ab$^{-1}$@500 GeV
$\Delta g_Y(t)/g_Y(t) = 9.9\%$

Tony Price, LCWS12
scaled from mH=120 GeV

1 ab$^{-1}$@1 TeV
$\Delta g_Y(t)/g_Y(t) = 3.1\%$

ILD / SiD DBD Studies

K. Fujii, Pheno2014, Pittsburgh, May 7, 2014
## Independent Higgs Measurements at ILC

Baseline ILC program

(M$_H = 125$ GeV)

<table>
<thead>
<tr>
<th>Ecm</th>
<th>250 GeV</th>
<th>500 GeV</th>
<th>1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity [fb]</td>
<td>250</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>polarization (e)</td>
<td>(-0.8, +0.3)</td>
<td>(-0.8, +0.3)</td>
<td>(-0.8, +0.2)</td>
</tr>
<tr>
<td>process</td>
<td>ZH</td>
<td>vvH(fusion)</td>
<td>ZH</td>
</tr>
<tr>
<td>cross section</td>
<td>2.6%</td>
<td>-</td>
<td>3%</td>
</tr>
<tr>
<td>$\sigma \cdot Br$</td>
<td>$\sigma \cdot Br$</td>
<td>$\sigma \cdot Br$</td>
<td>$\sigma \cdot Br$</td>
</tr>
<tr>
<td>H→bb</td>
<td>1.2%</td>
<td>10.5%</td>
<td>1.8%</td>
</tr>
<tr>
<td>H→cc</td>
<td>8.3%</td>
<td>13%</td>
<td>6.2%</td>
</tr>
<tr>
<td>H→gg</td>
<td>7%</td>
<td>11%</td>
<td>4.1%</td>
</tr>
<tr>
<td>H→WW*</td>
<td>6.4%</td>
<td>9.2%</td>
<td>2.4%</td>
</tr>
<tr>
<td>H→ττ</td>
<td>4.2%</td>
<td>5.4%</td>
<td>9%</td>
</tr>
<tr>
<td>H→ZZ*</td>
<td>18%</td>
<td>25%</td>
<td>8.2%</td>
</tr>
<tr>
<td>H→γγ</td>
<td>34%</td>
<td>34%</td>
<td>19%</td>
</tr>
<tr>
<td>H→μμ</td>
<td>100%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
ILC \( 250+500+1000 \)
Model-independent Global Fit for Couplings

33 $\sigma x BR$ measurements ($Y_i$) and $\sigma_{ZH}$ ($Y_{34,35}$)

$$\chi^2 = \sum_{i=1}^{35} \left( \frac{Y_i - Y'_i}{\Delta Y_i} \right)^2$$

$Y'_i = F_i \cdot \frac{g^2_{HA_i A_i} \cdot g^2_{HB_i B_i}}{\Gamma_0} \cdot (i = 1, \ldots, 33)$

$F_i = S_i \cdot G_i$

$S_i = \left( \frac{\sigma_{ZH}}{g^2_{HZZ}} \right), \left( \frac{\sigma_{\nu\bar{\nu}H}}{g^2_{HWW}} \right), \text{or} \left( \frac{\sigma_{t\bar{t}H}}{g^2_{Htt}} \right)$

$G_i = \left( \frac{\Gamma_i}{g^2_i} \right)$

- It is the recoil mass measurement that is the key to unlock the door to this completely model-independent analysis!
- Cross section calculations ($S_i$) do not involve QCD ISR.
- Partial width calculations ($G_i$) do not need quark mass as input.

We are confident that the total theory errors for $S_i$ and $G_i$ will be at the 0.1% level at the time of ILC running.
### Model-independent Global Fit for Couplings

#### Baseline ILC program

(M$_H$ = 125 GeV)

<table>
<thead>
<tr>
<th>coupling</th>
<th>250 GeV</th>
<th>250 GeV + 500 GeV</th>
<th>250 GeV + 500 GeV + 1 TeV</th>
</tr>
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<tr>
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<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>HWW</td>
<td>4.8%</td>
<td>1.1%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Hbb</td>
<td>5.3%</td>
<td>1.6%</td>
<td>1.3%</td>
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<tr>
<td>Hcc</td>
<td>6.8%</td>
<td>2.8%</td>
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<tr>
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<td>2.3%</td>
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<td>1.6%</td>
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<td>4%</td>
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<tr>
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<td>91%</td>
<td>16%</td>
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</tr>
<tr>
<td>Htt</td>
<td>-</td>
<td>14%</td>
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</tr>
<tr>
<td>HHH</td>
<td>-</td>
<td>83%(*)</td>
<td>21%(*)</td>
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*With H->WW* (preliminary), if we include expected improvements in jet clustering it would become 17%!

P(e-,e+)=(−0.8,+0.3) @ 250, 500 GeV

P(e-,e+)=(−0.8,+0.2) @ 1 TeV

250 GeV:  250 fb$^{-1}$
500 GeV:  500 fb$^{-1}$
1 TeV:  1000 fb$^{-1}$
Mass Coupling Relation
After Baseline ILC Program

Baseline ILC Program
250fb$^{-1}$ @ 250GeV
500fb$^{-1}$ @ 500GeV
1000fb$^{-1}$ @ 1000GeV

Notice the rare mode like $H \rightarrow \mu^+\mu^-$ and significant improvement in top Yukawa and self-coupling measurements.
**Model-independent Global Fit for Couplings**

**Luminosity Upgraded ILC**

\[ (M_H = 125 \text{ GeV}) \]

<table>
<thead>
<tr>
<th>coupling</th>
<th>250 GeV</th>
<th>250 GeV + 500</th>
<th>250 GeV + 500 GeV + 1 TeV</th>
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<td>HWW</td>
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<tr>
<td>Hbb</td>
<td>2.5%</td>
<td>0.8%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Hcc</td>
<td>3.2%</td>
<td>1.5%</td>
<td>1%</td>
</tr>
<tr>
<td>Hgg</td>
<td>3%</td>
<td>1.2%</td>
<td>0.93%</td>
</tr>
<tr>
<td>Hττ</td>
<td>2.7%</td>
<td>1.2%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Hγγ</td>
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<tr>
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<td>42%</td>
<td>10%</td>
</tr>
<tr>
<td>Γ</td>
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</tr>
<tr>
<td>Htt</td>
<td>-</td>
<td>7.8%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

| HHH      | -       | 46%(*)       | 13%(*)                    |

*) With H->WW* (preliminary), if we include expected improvements in jet clustering, it would become 10%!
Figure 1.17. The deviation in $\kappa_f = \xi_f^h$ in the 2HDM with Type I, II, X and Y Yukawa interactions are plotted as a function of $\tan\beta = v_2/v_1$ and $\kappa_V = \sin(\beta - \alpha)$ with $\cos(\beta - \alpha) \leq 0$. For the illustration purpose only, we slightly shift lines along with $\kappa_x = \kappa_y$. The points and the dashed curves denote changes of $\tan\beta$ by one steps. The scaling factor for the Higgs-gauge-gauge coupling constants is taken to be $\kappa_V^2 = 0.99, 0.95$ and 0.90. For $\kappa_V = 1$, all the scaling factors with SM particles become unity. The current LHC constraints, expected LHC and ILC sensitivities on (left) $\kappa_d$ and $\kappa_\ell$ and (right) $\kappa_u$ and $\kappa_\ell$ are added.
Self-Coupling

How did EW phase transition happen?

Contour plot of $\Delta \lambda_{hhh}/\lambda_{hhh}$ and $\varphi_c/T_c$ in the $m_\Phi$-$M$ plane

Figure 1.21. The region of strong first order phase transition ($\varphi_c/T_c > 1$) required for successful electroweak baryogenesis and the contour plot of the deviation in the triple Higgs boson coupling from the SM prediction [11], where $m_\Phi$ represents degenerated mass of $H$, $A$ and $H^\pm$ and $M$ is the soft-breaking mass of the discrete symmetry in the Higgs potential.
EWSB Summary
• The primary goal for the next decades is to uncover the secret of the EW symmetry breaking. This will open up a window to BSM and set the energy scale for the E-frontier machine that will follow LHC and ILC.

• Probably LHC will hit systematic limits at O(2-5%) for most of $\sigma \times BR$ measurements, being not enough to see the BSM effects if we are in the decoupling regime. Moreover, we need some model assumption to extract couplings from the LHC data.

• The recoil mass measurement at ILC unlocks the door to a fully model-independent analysis. To achieve the primary goal we hence need a 500 GeV LC for self-contained precision Higgs studies to complete the mass-coupling plot
  
  • starting from $e^+e^- \rightarrow ZH$ at $E_{cm} = 250$GeV,
  • then $t\bar{t}$bar at around 350GeV,
  • and then $ZHH$ and $t\bar{t}H$ at 500GeV.

• The ILC to cover up to 500 GeV is an ideal machine to carry out this mission (regardless of BSM scenarios) and we can do this completely model-independently with staging starting from 250GeV. We may need more data depending on the size of the deviation. The ILC has a luminosity upgrade potential.

• If we are lucky, some extra Higgs boson or some other new particle might be within reach already at ILC 500. Let’s hope that the upgraded LHC will make another great discovery in the next run.

• If not, we will most probably need the energy scale information from the precision Higgs studies. Guided by the energy scale information, we will go hunt direct BSM signals with a new machine, if necessary.
Last but Not Least

• So far, I have been focusing on the case where $X(125\text{GeV})$ alone would be the probe for BSM physics, but there is a good chance for the higher energy run of LHC to bring us more.

• It is also very important to stress that ILC, too, is an energy frontier machine. It will access the energy region never explored with any lepton collider. There can be a zoo of new uncolored particles or new phenomena that are difficult to find at LHC but can be discovered and studied in detail at ILC.

• For instance
  • Natural SUSY : naturalness prefers $\mu$ not far above $100\text{GeV}$

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2$$

→ light chargino/neutralinos will be higgsino-dominant and nearly degenerate
→ typically $\Delta m$ of $10 \text{ GeV}$ or less → very difficult for LHC!
**Higgsinos in Natural SUSY ($\Delta M$<$\text{a few GeV}$)**

**ILC as a Higgsino Factory**

**ISR Tagging**

Only very soft particles in the final states $\rightarrow$ Require a hard ISR to kill huge two-photon BG!

$500\text{fb}^{-1}$ @ $E_{cm}=500\text{GeV}$

$\text{Pol} (e^+,e^-) = (+0.3,-0.8)$ and $(-0.3,+0.8)$

$\delta(\sigma \times BR) \simeq 3\%$

$\delta M_{\tilde{\chi}^\pm_1} (M_{\tilde{\chi}_0^0}) \simeq 2.1(3.7)\text{ GeV}$

$\delta \Delta M (\tilde{\chi}^\pm_1, \tilde{\chi}_1^0) \simeq 70\text{ MeV}$

$\delta(\sigma \times BR) \simeq 1.5\%$

$\delta M_{\tilde{\chi}^\pm_1} (M_{\tilde{\chi}_0^0}) \simeq 1.5(1.6)\text{ GeV}$

$\delta \Delta M (\tilde{\chi}^\pm_1, \tilde{\chi}_1^0) \simeq 20\text{ MeV}$
Extracting M1 and M2

In the radiatively driven natural SUSY (RNS) scenario as in arXiv: 1404.7510, \( \Delta M \sim 10 \text{GeV} \), we can determine M1 and M2 to a few % or better, allowing us to test GUT relation!
SM up to $\Lambda_{\text{Planck}}$?

What if the Higgs properties would turn out to be just like those of the SM Higgs boson to the ILC precision and no BSM signal found?

We need to question then the range of validity of the SM. How far can the SM go?
Stability of SM Vacuum

With the 125GeV Higgs boson, the SM vacuum seems to be at a subtle point of meta-stability!

Does \( \lambda \) really become negative below \( \Lambda_{\text{Pl}} \)?
or \( \lambda(\Lambda_{\text{Pl}}) = 0 \)?

To answer this we need a precision \( m_t \) measurement!

**Top Pair Threshold**

Theoretically very clean measurement of \( m_t \)

\[ \Delta m_t(\overline{MS}) \approx 100 \text{ MeV} \]
\[ \Delta m_H = 30 \text{ MeV} \]

ILC pins down the location!
Conclusions

Whatever new physics is awaiting for us, clean environment, polarized beams, and excellent detectors to reconstruct W/Z/t/H in their hadronic decays will enable us to uncover the nature of the new physics through model-independent precision measurements and open up the way to high scale physics!

ILC Situation

- ILC TDR completed = Technology is ready
- A preferred candidate site in Japan chosen and site specific design started.
- ILC is now a project officially recognized by the Japanese government, a TF has been formed in MEXT (funding agency), and an official review process in MEXT is about to start.
- However, ILC is NOT a Japanese project, BUT an INTERNATIONAL project!
- The Japanese government has just started contacting potential partners in the world.
- International support at all levels, including the grass root level, is absolutely necessary to make ILC happen! We need to convince the government that the world HEP community is eager to realize ILC in the earliest possible timescale!
Backup
Main Production Processes
Single Higgs Production

Production cross section

ZH dominates at 250 GeV
(~80k ev: 250 fb^{-1})

vvH takes over at 500 GeV
(~125k ev: 500 fb^{-1})

Possible to rediscover the Higgs in one day!
Spin and CP Mixing
Measurements that compliment those at LHC

Search for small CP-odd admixture to a few %
CP-odd ZHH coupling is loop-induced, may not be the best way, though.

K. Fujii, Pheno2014, Pittsburgh, May 7, 2014
Model-dependent **Global Fit for Couplings**

7-parameter fit

Model Assumptions

\[ \kappa_c = \kappa_t \quad \text{and} \quad \Gamma_{\text{tot}} = \sum_{i \in \text{SM decays}} \Gamma_i^{\text{SM}} \kappa_i^2 \]

\[ \kappa_i := g_i / g_i^{(\text{SM})} \]

Results

<table>
<thead>
<tr>
<th>Facility</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC500</th>
<th>ILC500-up</th>
<th>ILC1000</th>
<th>ILC1000-up</th>
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<td>14,000</td>
<td>250/500</td>
<td>250/500</td>
<td>250/500/1000</td>
<td>250/500/1000</td>
</tr>
<tr>
<td>( \int L dt ) (fb(^{-1}))</td>
<td>300/expt</td>
<td>3000/expt</td>
<td>250+500</td>
<td>1150+1600</td>
<td>250+500+1000</td>
<td>1150+1600+2500</td>
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<tr>
<td>( \kappa_\gamma )</td>
<td>5 – 7%</td>
<td>2 – 5%</td>
<td>8.3%</td>
<td>4.4%</td>
<td>3.8%</td>
<td>2.3%</td>
</tr>
<tr>
<td>( \kappa_g )</td>
<td>6 – 8%</td>
<td>3 – 5%</td>
<td>2.0%</td>
<td>1.1%</td>
<td>1.1%</td>
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</tr>
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<td>( \kappa_W )</td>
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<td>0.21%</td>
<td>0.21%</td>
<td>0.2%</td>
</tr>
<tr>
<td>( \kappa_Z )</td>
<td>4 – 6%</td>
<td>2 – 4%</td>
<td>0.49%</td>
<td>0.24%</td>
<td>0.50%</td>
<td>0.3%</td>
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<tr>
<td>( \kappa_\ell )</td>
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<td>0.98%</td>
<td>1.3%</td>
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<td>0.51%</td>
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<td>( \kappa_u = \kappa_t )</td>
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<td>7 – 10%</td>
<td>2.5%</td>
<td>1.3%</td>
<td>1.3%</td>
<td>0.9%</td>
</tr>
</tbody>
</table>

Snowmass Higgs WG Report (Draft)
LHC + ILC
ILC greatly improves the LHC precisions and provides the necessary precision for the fingerprinting

For rare decays such as $H \rightarrow \gamma\gamma$, there is powerful synergy of LHC and ILC!
Hunting Ground for Extra Higgs Bosons

Figure 1.20. Regions below the curves are allowed by the constraints from unitarity and vacuum stability on the $\tan \beta - m_A$ plane for each fixed value of $\kappa_V^2$. For $M = m_A = m_H = m_{H^+}$ in the Type II and Type X 2HDMs. Expected excluded parameter spaces are also shown by blue (orange) shaded regions from the gluon fusion production and associate production of $A$ and $H$ with bottom quarks and tau leptons at the LHC with the collision energy to be 14 TeV with the integrated luminosity to be 300 fb$^{-1}$ (3000 fb$^{-1}$).

Self-coupling
Self-coupling Measurement
Weighting Method to Enhance the Sensitivity to $\lambda$

\[
\frac{d\sigma}{dx} = B(x) + \lambda I(x) + \lambda^2 S(x)
\]

irreducible  interference  self-coupling

**Observable:** weighted cross-section

\[
\sigma_w = \int \frac{d\sigma}{dx} w(x) dx
\]

**Equation for the optimal $w(x)$ (variational principle):**

\[
\sigma(x)w_0(x) \int (I(x) + 2S(x))w_0(x) dx = (I(x) + 2S(x)) \int \sigma(x)w_0^2(x) dx
\]

**General solution:**

\[
w_0(x) = c \cdot \frac{I(x) + 2S(x)}{\sigma(x)}
\]

c: arbitrary normalization factor
Expected Coupling Precision as a Function of Ecm

\[ E_{\text{cm}} \text{ [GeV]} \]

\[ \frac{\delta \lambda}{\lambda} \]

\[ L \propto E_{\text{cm}} \]

\[ 2 \text{ab}^{-1} \text{ at 1 TeV} \]
HL-ILC ?
ILC Stages and Upgrades

The current ILC design is rather conservative!


Blue: upgrade described in TDR

x4 upgrade @250GeV
### HL-ILC

<table>
<thead>
<tr>
<th>Center-of-mass energy</th>
<th>( E_{CM} ) (GeV)</th>
<th>1st Stage Higgs Factory</th>
<th>Baseline ILC, after Lumi Upgrade</th>
<th>High Rep Rate Operation</th>
</tr>
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<tbody>
<tr>
<td>Collision rate</td>
<td>( f_{\text{rep}} ) Hz</td>
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<td>5</td>
<td>10</td>
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<tr>
<td>Electron linac rate</td>
<td>( f_{\text{linac}} ) Hz</td>
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<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>( n_b )</td>
<td>1312</td>
<td>2625</td>
<td>2625</td>
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<tr>
<td>Pulse current</td>
<td>( I_{\text{beam}} ) mA</td>
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<tr>
<td>Average total beam power</td>
<td>( P_{\text{beam}} ) MW</td>
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<td>Estimated AC power</td>
<td>( P_{\text{AC}} ) MW</td>
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<td>160</td>
<td>200</td>
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<tr>
<td>Luminosity</td>
<td>( L \times 10^{34} \text{cm}^{-2}\text{s}^{-1} )</td>
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<th>Lumi(1) (fb(^{-1}))</th>
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<th>Ecm(2) (GeV)</th>
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<th>Lumi(3) (fb(^{-1}))</th>
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<td></td>
<td>+</td>
<td></td>
<td></td>
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<td>+</td>
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<td>+</td>
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<td>2500</td>
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<td>500</td>
<td>1600</td>
<td>+</td>
<td>1000</td>
<td>2500</td>
<td>5.8</td>
<td>1220</td>
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### Independent Higgs Measurements

**Luminosity Upgraded ILC**

(M$_H$ = 125 GeV)

K.Fujii, Pheno2014, Pittsburgh, May 7, 2014

<table>
<thead>
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<th>Ecm</th>
<th>250 GeV</th>
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<td>1000</td>
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<td>(-0.8, +0.3)</td>
<td>(-0.8, +0.2)</td>
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<td>process</td>
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<td>vvH(fusion)</td>
<td>ZH</td>
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<td>-</td>
<td>1.7%</td>
</tr>
<tr>
<td></td>
<td>σ·Br</td>
<td>σ·Br</td>
<td>σ·Br</td>
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<td>1%</td>
</tr>
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<td>7.2%</td>
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<td>6%</td>
<td>2.3%</td>
</tr>
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<td>3%</td>
<td>5.1%</td>
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<td>3%</td>
<td>5%</td>
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<td>H--&gt;μμ</td>
<td>46.6%</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>

250 GeV: 250 fb$^{-1}$
500 GeV: 500 fb$^{-1}$
1 TeV: 1000 fb$^{-1}$

250 GeV: 1150 fb$^{-1}$
500 GeV: 1600 fb$^{-1}$
1 TeV: 2500 fb$^{-1}$
Indirect BSM Searches
Top Quark

Anomalous Couplings in Open Top Production at 500 GeV

Figure 34: Predictions of various groups [40,42–44] on deviations from Standard Model couplings of the t quark within Randall-Sundrum Models. The cartoon is taken from [47].

Table 12: Sensitivities achievable at 68.3% CL for the anomalous $t\bar{t}V$ ($V = \gamma, Z$) couplings $\Delta \tilde{F}_{1V, A}^V$ and $\Delta \tilde{F}_{2V, A}^V$ of Eq. (59) at the LHC for integrated luminosities of 300 fb$^{-1}$, and the ILC with $\sqrt{s} = 500$ GeV (taken from Ref. [23]). Only one coupling at a time is allowed to deviate from its SM value. Table and caption have been copied from [16].
Two-Fermion Processes

Z’ Search / Study

ILC’s Model ID capability is expected to exceed that of LHC even if we cannot hit the Z’ pole.

Beam polarization is essential to sort out various possibilities.
Two-Fermion Processes

Compositeness

 Beam polarization is essential to sort out various possibilities.

Figure 26: Sensitivities (95% c.l.) of a 500 GeV ILC to contact interaction scales $\Lambda$ for different helicities in $e^+e^- \to$ hadrons (left) and $e^+e^- \to \mu^+\mu^-$ (right), including beam polarization \[18\].
ILC Situation in Japan
“Issues that could lead to particularly serious difficulties for the Sefuri site are that the route passes under or near a dam lake, and that the route passes under a city zone. Also, the lengths of access tunnels are longer for the Sefuri site than for the Kitakami site leading to a large merit for the latter in terms of cost, schedule, and drainage.”
Preferred Site selected