Physics opportunity at ILC

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Workshop on ILC
August 2, 2019, TIFR, Mumbai, India
1.1 Physics

The main purpose of JLC-I is to discover and study the Higgs boson and the top quark, which are the two missing constituents of the Standard Model.

The most exciting possibility is the discovery of a Higgs particle with a mass less than 200 GeV. This mass range is particularly interesting from the viewpoint of grand unified models with the grand desert hypothesis, which naturally explain charge quantization, anomaly cancellation, strengths of the gauge interactions, etc. Moreover, the Weinberg angle $\sin^2 \theta_W$, which has been precisely measured at LEP, agrees well with the prediction of its simplest supersymmetric extension originally introduced to solve the naturalness problem. Grand unified models with weak-scale supersymmetry predict at least one light Higgs boson, which cannot be missed at JLC-I with $\sqrt{s} = 300$ GeV.
GLC Project
September 2003
(before the discovery of the Higgs boson)
ILC since 2004

• By early 2000’s, it became a consensus among the world HEP community that an e+e- linear collider with the CM energy of about 500 GeV should be the next collider beyond the LHC.

• ICFA chose the cold technology for LC as a global project, and set up a global team (GDE) for design and coordination of R&D for the ILC.

• The ILC-TDR was published in June 2013. ICFA set up the Linear Collider Collaboration for engineering design phase.

• After the 13TeV run of the LHC experiment, the worldwide HEP community reached a consensus that the ILC should be built as a Higgs factory while keeping energy extendibility in November 2017.
Discovery of a Higgs boson

July 4, 2012 at CERN
Announcement of discovery of a Higgs boson at about 125 GeV

www.elsevier.com/locate/physletb
TeV is special

~1930’s

Discovery of neutrons
Two new forces (strong, weak) were introduced

~1970’s

Theory of three interactions based on one additional unknown force (electroweak symmetry breaking)

~2010’s

Discovery of a Higgs boson
What is the unknown force?

Early Universe

Big-Bang Nucleosynthesis

Quark-Hadron Transition

Electroweak Phase Transition

The Fermi constant

\[ G_F = \frac{1}{\sqrt{2} v^2} \]

Nambu’s Symmetry Breaking
Higgs boson is a key to new physics

Physics below TeV
- One Higgs doublet model
- Supersymmetry
- Grand Unified Theory
- Little Higgs Models (Composite Higgs models)
- Extra-dimensions
- Unification with gravity at low energy scale
- etc., etc.

Physics above TeV
- Unification with gravity

Physics at Planck scale
- New strong force

With Higgs boson(s)

Without
- Technicolor model

The property of the Higgs boson depends on how the Higgs field is incorporated in particle physics models beyond the TeV scale.
250 GeV is a Special Energy

Single Higgs production cross section maximum

Production Cross Section as a fun. of $E_{cm}$

$P(e^-, e^+)=(-0.8, 0.3)$, $M_h=125$ GeV

$250$ GeV: cross section maximum (~0.5 Million events for 2 ab$^{-1}$)
**Recent Development: EFT Analysis**

**Potential drawback:**

It has been said that $\Gamma_h$ (Higgs total width) necessary for absolute coupling normalization requires $>350\text{GeV}$.

**Solution:** \textit{EFT (Effective Field Theory)} to relate $hZZ$ and $hWW$ couplings

LHC Run II results suggest that 250 GeV is likely in the validity range of the EFT.

$W_L$ and $Z_L$ are NGBs from the Higgs sector. can use all the SM processes with $W$ and $Z$ to constrain the EFT coefficients.

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta \mathcal{L}$$

SU(2)xU(1) inv.

dim.6 operators

# EFT coefficients to decide: 17 @ ILC

This ILC number is quite tractable.

\textbf{Beam polarization doubles the number of usable observables.}

The importance of the $\sigma_{zh}$ measurement by recoil mass technique remains the same.

Cross section: small@250GeV
Higgs coupling measurements at ILC

ILC allows model-independent fit to extract all the major Higgs couplings.

Self-coupling: Not accessible at 250 GeV. Can reach 26% at 500 GeV.

Top Yukawa: Not accessible at 250 GeV. Can reach 3% at 550 GeV.
FIG. 1. Projected Higgs boson coupling uncertainties for the LHC and ILC using the model-dependent assumptions appropriate to the LHC Higgs coupling fit. The dark- and light-red bars represent the projections in the scenarios S1 and S2 presented in [9, 10]. The scenario S1 refers to analyses with our current understanding; the scenario S2 refers to more optimistic assumptions in which experimental errors decrease with experience. The dark- and light-green bars represent the projections in the ILC scenarios in similar S1 and S2 scenarios defined in [6]. The dark- and light-blue bars show the projections for scenarios S1 and S2 when data from the 500 GeV run of the ILC is included. The same integrated luminosities are assumed as for Figure 2. The projected uncertainties in the Higgs couplings to $\mu\mu$, $tt$, and the self-coupling are divided by the indicated factors to fit on the scale of this plot.
Power of Polarization

Impact of Luminosity, Energy and Polarisation
- HL-LHC e⁺e⁻ 2 ab⁻¹ 250 GeV polarised
- HL-LHC e⁺e⁻ 4 ab⁻¹ 500 GeV polarised
- HL-LHC e⁺e⁻ 5 ab⁻¹ 250 GeV unpolarised
- e⁺e⁻ 1.5 ab⁻¹ 350 GeV unpolarised

Model Independent Fit

LCC Physics WG

Precision of Higgs boson couplings [%]

Z, W, b, τ, g, c, Γₜₐₜ, Γₜ, γ, Zγ, μ, t, λ
We need to study Higgs couplings

**Supersymmetry (MSSM)**

- MSSM ($\tan\beta = 5, M_A = 700$ GeV)
- Upward shift only for down-type fermions

**Composite Higgs (MCHM5)**

- Minimal Composite Higgs Model 5 ($\phi = 1.5$ TeV)
- Downward shift for all the couplings

**Multi-verse? (Standard Model)**

- Standard Model
- No deviation at all
**Sensitivity to BSM**

ILC not only shows us the general direction but points to a specific direction

9 sample models and expected deviations (%)

<table>
<thead>
<tr>
<th>Model</th>
<th>$b\bar{b}$</th>
<th>$c\bar{c}$</th>
<th>$gg$</th>
<th>$WW$</th>
<th>$\tau\tau$</th>
<th>$ZZ$</th>
<th>$\gamma\gamma$</th>
<th>$\mu\mu$</th>
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</thead>
<tbody>
<tr>
<td>MSSM [37]</td>
<td>+4.8</td>
<td>-0.8</td>
<td>-0.8</td>
<td>-0.2</td>
<td>+0.4</td>
<td>-0.5</td>
<td>+0.1</td>
<td>+0.3</td>
</tr>
<tr>
<td>Type II 2HD [38]</td>
<td>+10.1</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0.0</td>
<td>+9.8</td>
<td>0.0</td>
<td>+0.1</td>
<td>+9.8</td>
</tr>
<tr>
<td>Type X 2HD [38]</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0.0</td>
<td>+7.8</td>
<td>0.0</td>
<td>0.0</td>
<td>+7.8</td>
</tr>
<tr>
<td>Type Y 2HD [38]</td>
<td>+10.1</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0.0</td>
<td>-0.2</td>
<td>0.0</td>
<td>0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>Composite Higgs [39]</td>
<td>-6.4</td>
<td>-6.4</td>
<td>-6.4</td>
<td>-2.1</td>
<td>-6.4</td>
<td>-2.1</td>
<td>-2.1</td>
<td>-6.4</td>
</tr>
<tr>
<td>Little Higgs w. T-parity [40]</td>
<td>0.0</td>
<td>0.0</td>
<td>-6.1</td>
<td>-2.5</td>
<td>0.0</td>
<td>-2.5</td>
<td>-1.5</td>
<td>0.0</td>
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<tr>
<td>Little Higgs w. T-parity [41]</td>
<td>-7.8</td>
<td>-4.6</td>
<td>-3.5</td>
<td>-1.5</td>
<td>-7.8</td>
<td>-1.5</td>
<td>-1.0</td>
<td>-7.8</td>
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<tr>
<td>Higgs-Radion [42]</td>
<td>-1.5</td>
<td>-1.5</td>
<td>+10.0</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.0</td>
<td>-1.5</td>
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<tr>
<td>Higgs Singlet [43]</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
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</tbody>
</table>

All new particles unlikely to be within the reach of the HL-LHC

$\rightarrow$ The only probe would be precision measurements of the Higgs couplings

**Discrimination power in $\sigma$**

<table>
<thead>
<tr>
<th>Model</th>
<th>Discrimination in $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>5.8</td>
</tr>
<tr>
<td>pMSSM</td>
<td>6.5</td>
</tr>
<tr>
<td>2HDM-II</td>
<td>6.2</td>
</tr>
<tr>
<td>2HDM-X</td>
<td>6.2</td>
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<tr>
<td>2HDM-Y</td>
<td>11.3</td>
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<tr>
<td>Composite</td>
<td>3.9</td>
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<tr>
<td>LHT-6</td>
<td>4.3</td>
</tr>
<tr>
<td>LHT-7</td>
<td>5.4</td>
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<tr>
<td>Radion</td>
<td>6.1</td>
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<tr>
<td>Singlet</td>
<td>3.5</td>
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$\rightarrow$ 3 $\sigma$ sensitivities to most models @ 250 GeV

<table>
<thead>
<tr>
<th>Model</th>
<th>Discrimination in $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>9.3</td>
</tr>
<tr>
<td>pMSSM</td>
<td>16.4</td>
</tr>
<tr>
<td>2HDM-II</td>
<td>8.2</td>
</tr>
<tr>
<td>2HDM-X</td>
<td>18.2</td>
</tr>
<tr>
<td>2HDM-Y</td>
<td>6.6</td>
</tr>
<tr>
<td>Composite</td>
<td>6.9</td>
</tr>
<tr>
<td>LHT-6</td>
<td>9.3</td>
</tr>
<tr>
<td>LHT-7</td>
<td>9.8</td>
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<tr>
<td>Radion</td>
<td>5.2</td>
</tr>
<tr>
<td>Singlet</td>
<td>10.7</td>
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$\rightarrow$ 5 $\sigma$ sensitivities to almost all models @ 500 GeV
### Comparisons

<table>
<thead>
<tr>
<th></th>
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<tr>
<td>ILC</td>
<td>ee</td>
<td>0.25</td>
<td>2</td>
<td>11</td>
<td>129 (upgr. 150-200)</td>
<td>4.8-5.3 GICLU + upgrade</td>
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<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>4</td>
<td>10</td>
<td>163 (204)</td>
<td>7.98 GICLU</td>
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<tr>
<td></td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
<td>300</td>
<td>?</td>
</tr>
<tr>
<td>CLIC</td>
<td>ee</td>
<td>0.38</td>
<td>1</td>
<td>8</td>
<td>168</td>
<td>5.9 GCHF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>2.5</td>
<td>7</td>
<td>(370)</td>
<td>+5.1 GCHF</td>
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<tr>
<td></td>
<td></td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>(590)</td>
<td>+7.3 GCHF</td>
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<tr>
<td>CEPC</td>
<td>ee</td>
<td>0.091+0.16</td>
<td>16+2.6</td>
<td></td>
<td>149</td>
<td>5 G$</td>
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<tr>
<td></td>
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<td>0.24</td>
<td>5.6</td>
<td>7</td>
<td>266</td>
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<td>FCC-ee</td>
<td>ee</td>
<td>0.091+0.16</td>
<td>150+10</td>
<td>4+1</td>
<td>259</td>
<td>10.5 GCHF</td>
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<tr>
<td></td>
<td></td>
<td>0.24</td>
<td>5</td>
<td>3</td>
<td>282</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.365 (+0.35)</td>
<td>1.5 (+0.2)</td>
<td>4 (+1)</td>
<td>340</td>
<td>+1.1 GCHF</td>
</tr>
<tr>
<td>LHeC</td>
<td>ep</td>
<td>60 / 7000</td>
<td>1</td>
<td>12</td>
<td>(100)</td>
<td>1.75 GCHF</td>
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<tr>
<td>FCC-hh</td>
<td>pp</td>
<td>100</td>
<td>30</td>
<td>25</td>
<td>580 (550)</td>
<td>17 GCHF (+7 GCHF)</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>pp</td>
<td>27</td>
<td>20</td>
<td>20</td>
<td></td>
<td>7.2 GCHF</td>
</tr>
</tbody>
</table>

From “Accelerator Summary”
at Open Symposium towards updating the European Strategy for Particle Physics May 13-16, 2019, Granada, Spain
Figure 1: The luminosities of the ILC as functions of energy. Those of other $e^+e^-$ colliders are also shown. The numbers are per IP, while the effect of polarization is not included.
From “Summary: Electroweak Session” at Open Symposium towards updating the European Strategy for Particle Physics, May 13-16, 2019, Granada, Spain

“All ee colliders achieve major (and comparable) improvements in their first stage already in proving Higgs sector compared to HL-LHC”
Example of Non-Higgs Process that plays an important role in the EFT fit

$e^+e^- \rightarrow W^+W^-$ (Triple Gauge Couplings)

Figure 11: TGC precisions for LEP 2, Run1 at LHC, HL-LHC and the ILC at $\sqrt{s} = 250$ GeV with 2000 fb$^{-1}$ luminosity (ILC 250) using one parameter fits (a) and for LEP 2 and ILC 250 using three parameter fits (b).
WIMP Dark Matter Search @ ILC

Weakly Interacting Massive Particle

1. Higgs Invisible Decay

Effective when the Dark Matter particle interacts with the Higgs boson

\[ M_{DM} < M_h / 2 \]

- **ILD Simulation**
  \[ \sqrt{s} = 250 \text{ GeV} \]
  \[ \text{pol}(e^-,e^+) = (+0.8,-0.3) \]
  \[ 250 \text{ fb}^{-1} \]

- **Sensitivity**
  - **O(10)** more sensitive than HL-LHC

2. Mono-photon Search

Sensitive to various types of Dark Matter particles

Effective in particular for DM particles which couple mostly to EW gauge bosons and leptons and hence difficult to find at the LHC.

- **Light yellow region** = to be left for ILC (after future direct searches including HL-LHC)
Physics beyond 250 GeV ILC

- Important measurements
  Top mass at the top threshold
  Higgs self coupling, ttH coupling beyond 500 GeV
- Top anomalous coupling
- Extension of new particle search areas

The energy upgrade path can be decided based on the outcome of 250 GeV ILC.
Top Yukawa coupling drives the 4-point Higgs coupling ($\lambda$) to negative!

→ The true vacuum could be somewhere else at a high $\phi$ value.

The current values of $m_t$ and $m_h$ seem to be in subtle point of meta-stability!

Does $\lambda$ go to negative below $\Lambda_P$? or $\lambda(\Lambda_P) = 0$ (suggesting new principle) ?

To answer this, we need precision $m_t$ measurement!

At LHC, theory error limits the precision to $\sim 500$ MeV.

TTbar Threshold Scan @ILC allows very clean measurement of theoretically well defined $m_t$

**ILC pinpoints the vacuum location**

$\Delta m_t(M_S) \lesssim 50$ MeV

$\Delta m_H = 14$ MeV

arXiv:1205.6497, Degrassi et al.
Top EW coupling measurements

An order of magnitude improvements from HL-LHC expectations.
Higgs Self-Coupling

The **Higgs cubic self-coupling** is at the heart of EWSB, so should be measured in its own right!

There are **two ways to measure it** at ILC

- Small cross section
- **Presence of irreducible BG diagrams that dilute the self-coupling contribution!**
- **Separation of BSM effects that appear other than in self-coupling (possible in EFT: same impossible at LHC)**

Challenging even at ILC because of

**ILC**

<table>
<thead>
<tr>
<th>Energy</th>
<th>500 GeV</th>
<th>+ 1 TeV</th>
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<tbody>
<tr>
<td>Snowmass</td>
<td>46%</td>
<td>13%</td>
</tr>
<tr>
<td>H20</td>
<td>26%</td>
<td>10%</td>
</tr>
</tbody>
</table>

**CLIC**

<table>
<thead>
<tr>
<th>Energy</th>
<th>1.4 TeV</th>
<th>+3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1.5 ab⁻¹)</td>
<td>21%</td>
<td>10%</td>
</tr>
<tr>
<td>(2 ab⁻¹)</td>
<td>(arXiv: 1307.5288)</td>
<td></td>
</tr>
</tbody>
</table>

H20 arXiv: 1506.07870
J. Tian, LC-REP-2013-003
C. Dürig @ ALCW16
M. Kurata, LC-REP-2014-025

If +100% deviation as possible in EWBG scenario, Δλ/λ=14%!
EW Baryogenesis?

e.g.: 2 Higgs Doublet Model (2HDM)

Region where EW baryogenesis is possible

$\lambda_{2\text{HDM}} / \lambda_{\text{SM}} \%$

$\varphi_c/T_c$

Minimum value of HHH coupling

$\Delta \varphi$ at different $\psi_{\text{CP}}$

Senaha, Kanemura

Measurement of HHH coupling at ILC

At 500 GeV signal and background diagrams constructively interfere. $\rightarrow$ **If there is 100% upward shift** $\rightarrow \Delta \lambda / \lambda = 14\%$

Measuring CP in $H \rightarrow \tau^+ \tau^-$ at ILC

CP from polarimeters: taus from spin 0 parent

$\theta_{\pm}$, $\varphi_{\pm}$ direction of $h_{\pm}$ with respect to $\tau^-$ boost in $\tau^-$ rest frame

$\Delta \varphi$ angle between polarimeter planes

$\psi_{\text{CP}}$ CP mixing angle we want to measure

$2 a b^{-1} @ 250 \text{ GeV}$

$\delta \psi_{\text{CP}} \sim 4^\circ$

D. Jeans 2018
Summary

• A consensus has been reached among the high energy physics community that a Higgs Factory is the highest priority for the next global machine.

• ILC at 250 GeV promises excellent performance as a Higgs Factory. Electron polarizations are essential tool.

• ILC 250 also offers various opportunities for discoveries, ex. dark matter search.

• There are important physics programs beyond 250 GeV. Future energy upgrade path should be decided based on outcome of the 250GeV program.