Physics at the International Linear Collider

Maxim Perelstein, Cornell
PHENO-16, Pittsburgh, May 11 2016

based on work by LCC Physics Working Group

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“Physics Case for the ILC”, arXiv:1506.05992
ILC Proposal

- 20 years of R&D, key technologies demonstrated
- Technical Design Report (TDR) completed in 2013
- 5 volumes, incl. Physics, Accelerator, Detectors (arXiv)

**ILC Accelerator Concept**
A. Yamamoto, 160120

- Geant4-based FullSym, incl. beam effects

**Parameters**

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.M. Energy</td>
<td>250-500 GeV</td>
</tr>
<tr>
<td>Length</td>
<td>31 km</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$1.8 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
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<tr>
<td>Repetition</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Beam Pulse Period</td>
<td>0.73 ms</td>
</tr>
<tr>
<td>Beam Current</td>
<td>5.8 mA (in pulse)</td>
</tr>
<tr>
<td>Beam size ($y$) at FF</td>
<td>5.9 nm</td>
</tr>
<tr>
<td>SRF Cavity G. $Q_0$</td>
<td>31.5 MV/m $Q_0 = 1 \times 10^{10}$</td>
</tr>
</tbody>
</table>

**e- Polarization** 80%
**e+ Polarization** 30%
## ILC ML Parameters, demonstrated in TDR

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Parameter</th>
<th>Unit</th>
<th>Demonstrated</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SRF:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average accelerating gradient</td>
<td>31.5 (±20%)</td>
<td>MV/m</td>
<td>DESY, FNAL, JLab, Cornell, KEK,</td>
</tr>
<tr>
<td>Cavity Q₀</td>
<td>10⁹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Cavity qualification gradient)</td>
<td>35 (±20%)</td>
<td>MV/m</td>
<td>DESY-FLASH), KEK-STF</td>
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<tr>
<td>Beam current</td>
<td>5.8</td>
<td>mA</td>
<td>DESY-FLASH), KEK-STF</td>
</tr>
<tr>
<td>Number of bunches per pulse</td>
<td>1312</td>
<td></td>
<td>DESY</td>
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<tr>
<td>Charge per bunch</td>
<td>3.2</td>
<td>nC</td>
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<tr>
<td>Bunch spacing</td>
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<td>ns</td>
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<td>Beam pulse length</td>
<td>730</td>
<td>ms</td>
<td>DESY, KEK</td>
</tr>
<tr>
<td>RF pulse length (incl. fill time)</td>
<td>1.65</td>
<td>ms</td>
<td>DESY, KEK, FNAL</td>
</tr>
<tr>
<td>Efficiency (RF→beam)</td>
<td>0.44</td>
<td></td>
<td></td>
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<tr>
<td>Pulse repetition rate</td>
<td>5</td>
<td>Hz</td>
<td>DESY, KEK</td>
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<tr>
<td><strong>Nano-bam:</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ILC-FF beam size (y)</td>
<td>5.9</td>
<td>nm</td>
<td>KEK-ATF</td>
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<tr>
<td>KEK-ATF-FF equiv. beam size (y)</td>
<td>37 (44 reached)</td>
<td>nm</td>
<td>KEK-ATF</td>
</tr>
</tbody>
</table>

[slide: Akira Yamamoto]
ILC Site Candidate Location in Japan: Kitakami

- Preferred site selected by JHEP community,
- Endorsed by LCC, in 2013

-Site-specific design in progress
-Project currently being evaluated by Japan’s Ministry for Science and Education (MEXT)
4.1 Higgs couplings to fermions and gauge bosons

In this section we present some examples of how important physics results evolve in time for the
shutdowns at the time the shutdown starts. It is assumed that linac and damping ring installation occur in parallel and
The shutdown is for the TDR luminosity upgrade, where the number of bunches per
A major 18 month shutdown is assumed for the luminosity upgrade.

Table 7: Scenario H-20: Sequence of energy stages and their real-time conditions.

Figure 4: Accumulation of integrated luminosity versus real time for scenario H-20.

Table 8: Scenario I-20: Sequence of energy stages and their real-time conditions.

Integrated Luminosities [fb]

ILC Operating Scenarios

ILC Parameters Joint Working Group

T. Barklow, J. Brau, K. Fujii, J. Gao, J. List, N. Walker, K. Yokoya

arXiv:1506.07830

Table 3: Integrated luminosities per beam helicity configuration resulting from the fractions in
sharing listed in table 2 for all scenarios.

Integrated luminosity with sgn(P(e^-), P(e^+)) =

\[ \frac{\int \beta^2 dt}{\int \beta^{-1} \, dt} = \begin{cases} +1 & (\beta^+), \\ +1 & (\beta^-), \\ -1 & (\beta^+), \\ -1 & (\beta^-) \end{cases} \]

\[ \int \beta^2 dt = \frac{\int \beta^{-1} \, dt}{\int \beta^{-1} \, dt} = \begin{cases} +1 & (\beta^+), \\ +1 & (\beta^-), \\ -1 & (\beta^+), \\ -1 & (\beta^-) \end{cases} \]

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e+e- vs. Hadron Collider

Energy Range accessible to the ILC is “covered” by the LHC, but:

- **LHC:** Cross Section
  - Oligarchy - the Strong dominate the Weak
  - E.g. \( \frac{\sigma(H)}{\sigma_{\text{total}}} \sim 10^{-10} \)

- **ILC:** Cross Section
  - Democracy
  - E.g. \( \frac{\sigma(H)}{\sigma_{\text{total}}} \sim 10^{-2} \)

LHC: messy events due to soft QCD, pile-up

ILC: clean, low-occupancy environment

**e+e-** machine enables **precision studies** of Higgs & Top and **“hermetic”** searches for **new physics**
Higgs Studies at the ILC

- H20 run scenario corresponds to \( \sim 0.6M \) H @ 250 and 1M @ 500 GeV
- Measure many SM Higgs couplings at \( \sim 1\% \) level or better, in a model-independent way
- Highlights of the program:
  - Precise Higgstrahlung (Zh) measurement @ 250 GeV
  - WW fusion measurements @ 350 and 500 GeV
  - Direct measurement of \( tth \) coupling @ 500 (550?) GeV
Precision Higgsstrahlung

- Identify $Zh$ events by reconstructing recoil mass $M_X^2 = (p_{CM} - (p_{\ell^+} + p_{\ell^-}))^2$

- No observation of the Higgs is needed → unbiased, model-independent measurement of cross section

- Directly infer coupling $g_Z$

- In contrast, LHC rates $\propto \frac{\Gamma(h \to ZZ^*)}{\Gamma_{tot}}$

- Total Higgs width too small to be measured directly, rate-to-coupling conversion is based on some assumptions about $\Gamma_{tot}$
W Fusion and Higgs Width

- SM Higgs width ~6 MeV too small for a direct measurement

- Indirect, but model-independent, determination of $\Gamma_{\text{tot}}$ at ILC:
  - Measure @ 250 GeV: $\text{Br}(b\bar{b}) = \sigma(hZ, h \to b\bar{b})/\sigma_{\text{tot}}(hZ)$
  - Measure @ 500 GeV: $\sigma(WW \to h \to b\bar{b}) = \sigma(WW \to h)\text{Br}(b\bar{b})$
  - Combine to infer $\sigma(WW \to h) \rightarrow g_W \rightarrow \Gamma(WW^*)$
  - Measure @ 250 GeV: $\text{Br}(WW) = \sigma(hZ, h \to WW^*)/\sigma_{\text{tot}}(hZ)$
  - Extract $\Gamma_{\text{tot}} = \Gamma(WW^*)/\text{Br}(WW^*)$ (<2% precision!)
  - Infer couplings from Br measurements: $\Gamma(X) = \Gamma_{\text{tot}}\text{Br}(X) \rightarrow g_X$
Higgs Couplings Summary

Projected Higgs coupling precision (7-parameter fit)

- HL-LHC 14 TeV, 3000 fb
- ILC 500 GeV, 500 fb

Projected precision of Higgs coupling and width (model-independent fit)

- ILC 500 GeV, 500 fb
- ILC @ HL-LHC, 3000 fb

Constrained 7-parameter Fit
(for comparison w/LHC)

- RED - “initial” ILC running, 8 years
- ORANGE - “full” ILC running, 20 years
- BLUE - use HL-LHC measurement of $\frac{Br(h \rightarrow \gamma\gamma)}{Br(h \rightarrow ZZ)}$

Model-Independent Fit
(only possible @ ILC!)

- $K_t \rightarrow 3\%$ if run @ 550 GeV

“Higgs Portal” invisible or exotic decays
Higgs: Implications

- **Naturalness** of the EW scale is a major open issue [see N. Craig’s talk]
- Any extension of the SM that addresses EW naturalness must modify Higgs properties
- Weakly-coupled solutions (SUSY, Little H, Twin H) predict “top partners”, mass < TeV, coupling to H fixed by divergence cancellation argument

**COLORED** top partners (SUSY, Little H): LO shifts in $k_g, k_\gamma$

**COLORLESS** top partners (Twin H): NLO shift in $k_z$

\[ \delta R_g = 1\% \Rightarrow m_T \approx 1.3 \text{ TeV}, \text{FT} \sim 1\% \]

interpretation requires an independent top Yukawa measurement @ ILC-500!

No sensitivity at the LHC!

[Craig, Englert, McCullough, ‘13]
Stops: Direct (LHC) vs. Indirect (ILC)

Figure 6: As in Fig. 5 with the addition of projected conservative (dotted) and optimistic (dotdashed) sensitivity from $h!gg$ measurement shown in purple. Absolute deviations are shown but it should be kept in mind that the $h!gg$ corrections are positive for small $A$-terms (central region of left-hand plot and all of right hand plot) and negative for large $A$-terms (large mass splittings).

Dependence of the limit on $m_{\tilde{\tau}^0_1}$ is relatively weak, but as in the case of the cross section limit it may be substantially eroded by mixed branching ratios, three-body decays, or changes in the LSP identity. Also, removing the assumption of R-parity conservation drastically weakens the bounds. For example, if the stops decay to two jets via the RPV $UDD$ operator, all stop events result in purely hadronic final states buried under the large QCD background. Currently there is no LHC bound on this scenario [55]. In both cases, the difficulty faced by direct searches is not statistics – in fact the LHC Run-1 would already have produced a large sample of stops in these scenarios – but rather the difficulty of separating signal from background. This indicates that these scenarios will remain challenging for the LHC in Run-2 and beyond, and may well still be unconstrained at the time the Higgs factory becomes operational.

In addition to Higgsstrahlung measurement, the Higgs factory can perform other indirect searches for stop squarks. The leading sensitivity would be due to modifications of the $h!gg$ decays arising from loops of heavy stops. To compare the sensitivities, we again consider a “conservative” and an “optimistic” scenario, assuming a 4.6% and 1.6% precision in the measurement of $\langle h!gg \rangle$. (The two numbers correspond to the estimates of the Snowmass report [4] for the “ILC-500” and “TLEP-350” scenarios, respectively.) In Fig. 6 we compare the reach of the Higgs factory for stops via $h!gg$ and Higgsstrahlung measurements. It is clear that $h!gg$ has the higher sensitivity throughout the parameter space. Note that the “blind spot” is common for both measurements, since it is due to the suppression of the
Higgs: More Implications

- **Composite Higgs** models (Little H, H as A5 in 5D, ...) need H to be a pseudo-NGB of a new global symmetry

- This generically leads to suppression of H couplings: 
  \[
  h \rightarrow f \sin \frac{h}{f} \quad \Rightarrow \quad g \rightarrow g \sqrt{1 - \frac{\nu^2}{f^2}}
  \]

- 1-5% level if compositeness scale \( \sim \)TeV

- In many models H mixes w/extra scalars (e.g. 2HDM, MSSM, NMSSM) resulting in coupling shifts, which can be either direction

- Pattern of deviations in H couplings can hint at the nature of the underlying theory

[Asner, Barklow, et.al. ’13]
Higgs Formfactors

In addition to coupling shifts, new physics induces d>4 operators:

\[ \mathcal{L}_{\text{pre-EWSB}} = \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i \]

\[ \mathcal{O}_{WW} = g^2 |H|^2 W_{\mu\nu}^a W^{a,\mu\nu} \]
\[ \mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \]
\[ \mathcal{O}_{WB} = gg' H^\dagger \sigma^a HW_n^a B_{\mu\nu} \]
\[ \mathcal{O}_H = \frac{1}{2} (\partial_\mu |H|^2)^2 \]
\[ \mathcal{O}_T = \frac{1}{2} (H^\dagger \tilde{D}_\mu H)^2 \]
\[ \mathcal{O}_{LL}^{(3)\ell} = (i H^\dagger \sigma^a \tilde{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L) \]
\[ \mathcal{O}_{LL}^{(3)\ell} = (\bar{L}_L \gamma_\mu \sigma^a L_L)(\bar{L}_L \gamma^\mu \sigma^a L_L) \]
\[ \mathcal{O}_L^{\ell} = (i H^\dagger \tilde{D}_\mu H)(\bar{L}_L \gamma^\mu L_L) \]
\[ \mathcal{O}_R^{\ell} = (i H^\dagger \tilde{D}_\mu H)(\bar{e}_R \gamma^\mu e_R) \]

\[ \delta \sigma/\sigma = 0.5\%/0.1\% \]

[Craig, Farina, McCullough, MP, ‘14]
[see also Beneke, Boito, Wang, ’14; Craig, Gu, Liu, Wang’15]
Electroweak Phase Transition

- At high temperature, EW symmetry is restored.
- Phase transition occurred at $kT \sim 100 - 1000 \text{ GeV}$, $T \sim 10^{15} \text{ K}$, $t \sim 10^{-10} \text{ sec}$.
- Baryon asymmetry may have been generated during this phase transition IF it was strongly 1st-order (non-equilibrium - Sakharov’s cond.)
- In the SM, symmetry breaking is a cross-over, EW baryogenesis not possible.
- New physics coupled to Higgs can change the dynamics of the phase transition, make it 1st order.
- This new physics will generically also change T=0 Higgs couplings.
- Predicted Higgs coupling deviations in most models large enough to show up at the ILC.

Example: “LH Stau” model

[A. Katz, MP, ’14]

$\Delta \kappa_V = 0.8 - 1.2\%$
cf. ILC precision 0.2-0.4%
Higgs Self-Coupling

- ILC-500 is sensitive to $h^3$ coupling
- First test of Higgs potential shape!
- Hard; $\sim 30\%$ measurement at the ILC-500
- However, large shifts expected in models w/1st order phase transition: $\sim 100\%$ not unusual
- 1 TeV upgrade would increase precision to $\sim 10\%$

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Figure 1: SM with a single extra scalar. Models with a “bumpy” zero-temperature Higgs potential are shown by (blue) circles, and those without the bump by (red) crosses. (Left panel) The strength of the first-order EWPT $\varphi$, defined in Eq. (15), vs. Higgs cubic self-coupling. (Right panel) Higgs cubic self-coupling vs. Higgs mass for points exhibiting a strong first-order EWPT, $\varphi > 1$. In both plots, the Higgs self-coupling is normalized to the one-loop SM expectation for the same $m_h$.

Since strong first-order EWPT can only occur for $\varphi$ in the 500 GeV–1 TeV range, the correction term is large for these points. (The one-loop corrections to Eq. (23) are at most about 10\% in our scan.) In addition, as Fig. 4 indicates, there is a clear and strong correlation between this coupling and the strength of the EWPT.

4 A Model with Tree-Level Higgs-Singlet Mixing

In all examples studied above, the SM-like Higgs field $h$ was the only field that acquired an expectation value during the EWPT. If other scalar fields are present, they may change their value in the same transition, so that the order parameter for the EWPT is effectively a linear combination of $h$ and other fields. Of particular interest are models with extra gauge-singlet scalars, such as the NMSSM, certain Little Higgs models, and others. At low temperatures, both singlet and Higgs vevs are generically non-zero. At high temperatures, the Higgs vev is driven to zero, and although the singlet vev typically remains non-zero, the EWPT involves changes in both vevs. Since the zero-temperature singlet potential is not restricted to even-degree polynomials by gauge invariance, it may contain cubic terms, which can naturally produce large “bumps” and lead to strong first-order EWPT. We will...
Top Mass

“350 GeV” running is actually a scan across the t-tbar threshold

- Top threshold scan provides a precision study of the t-tbar quasibound state - the “Hydrogen atom” of QCD

- QCD calculations of the threshold shape up to N^3LO  [Beneke et. al., ’15]

- Precise theoretical definition and experimental determination of the top mass

\[ \delta m_t(1S) = 17 \text{ MeV}, \delta \Gamma_t = 26 \text{ MeV}, \delta y_t = 4.2\% \]

  [Seidel et. al.’13; Horiguchi et.al., ’13]

- Will address (in)stability of the SM Higgs vacuum (assuming no new physics relevant up to the GUT scale)
Top Electroweak Couplings

- t-tbar production @ 500 GeV is directly sensitive to the top coupling to the Z

- 1%-level measurements

- Beam polarization allows to separately measure couplings to $t_L$ and $t_R$

- Important e.g. in composite Higgs models where $t_L$ and $t_R$ typically have different degree of compositeness

- Reach in ~20 TeV range for KK scale in RS-type models
Direct New Particle Searches

- ILC provides an almost “hermetic” search for any new particles coupled to EW current within kinematic reach
- Example: Higgsino LSP + large gap
- Challenging at the LHC: Electroweak production, no cascades rely on monojet+MET signature
- Discovery reach only ~100 GeV at HL-LHC
- ILC uses photon ISR to tag this signal
Dark Matter Searches

• DM coupled to electrons can be pair-produced at the ILC

• Use ISR photon to tag such events

• SM background can be calculated precisely and normalized by changing beam polarization

• In effective operator formalism, probe different operators than at the LHC, w/ scale reach comparable or higher

• Complementary to direct and indirect searches

[Chae, MP,’12]
[Chaus, List, Titov, to appear]

[Snowmass DM Completeness WG,’13]

[WMAP Ω_{dm} \Rightarrow x \Rightarrow e^{-} \Rightarrow e^{+} \Rightarrow ILC \sigma(\gamma + \bar{f})]

[Birkedal, Matchev, MP,’04]
Summary

- ILC will explore $e^+e^-$ collisions in the 250-500 GeV energy range
- High-precision, model-independent determination of Higgs couplings
- Precise top mass+coupling measurements
- “Hermetic” direct searches for new physics up to kinematic reach

Unique opportunity to learn more about physics at the EW scale, and (hopefully) go beyond the SM
Backup slides
Linear or Circular?

Luminosity vs Energy

[Plot: M. Zanetti]

Wednesday, May 11, 16