Higgs Physics at the ILC

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Outline
• Physics at the ILC
• Higgs as a probe for new physics
• Higgs measurement precision at the ILC
International Linear Collider

e^+ e^- Energy Frontier
250-500 GeV & 1 TeV upgrade

December 2012: Technical Design Report
→ ILC technology ready in 2013
Physics at the ILC

Higgs Factory
- Observe vacuum condensation
- Verify origin of mass
- Multiple Higgs? (e.g. SUSY)
- Discover new physics

Top Factory
- Why is the top quark so heavy?
- Precision top mass measurements

Electroweak Unification

Mass Generation

Spontaneous Symmetry Breaking

Search for New Physics
- Search for dark matter
- Colorless new particles (heavy Higgs, Z’ …)
- Direct and indirect searches

Physics Beyond the Standard Model

References

The Higgs Puzzle

The unique roles of Higgs in the SM

W, Z boson mass

Fermion mass

Same Higgs?

Vacuum condensation

HWW, HZZ coupling

Self-coupling

Yukawa coupling

ILC will fully uncover the Higgs sector
Higgs Sector and New Physics

New physics affects the Higgs sector

High

Extra Dim.  SUSY  Strong Dynamics

Low

SM + Singlet  SM + Doublet  SM + Triplet

Extended Higgs Sector

May be able to solve well-known BSM phenomena: dark matter, neutrino mass, baryon asymmetry, etc
**“Finger-printing” Models**

Higgs Coupling Precision with ILC Full Program (Model-Independent Analysis)

**Singlet Mixing**

**MSSM / Type II 2HDM**

Precision measurement of all Higgs couplings → Identify pattern of new physics
Synergy in Collider Experiments

Complementary approaches to new physics
Supersymmetry

- **Colored SUSY** constrained by LHC (must be heavy if exists)
- Currently **no universal limits** on **colorless** particles (sleptons, gauginos)
- **ILC** will probe the **colorless** light SUSY sector

**Typical cMSSM scenario**

**Typical GMSB scenario**

**Typical AMSB scenario**

- **Colored SUSY** constrained by LHC (must be heavy if exists)
- Currently **no universal limits** on **colorless** particles (sleptons, gauginos)
- **ILC** will probe the **colorless** light SUSY sector
Physics at the ILC

250~500 GeV
Higgs Factory
Observe vacuum condensation
Verify origin of mass
Multiple Higgs? (e.g. SUSY)
Discover new physics

250~ GeV
Search for New Physics
Search for dark matter
Colorless new particles (heavy Higgs, Z’ …)
Direct and indirect searches

350 GeV
Top Factory
Why is the top quark so heavy?
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Physics Beyond the Standard Model
ILC Staging Strategy

• **ILC** can *gradually* increase the CM energy by **extending the Main Linac**
  - Cost does not scale linearly due to facilities such as Damping Rings

• **Physics** determines the target energy: *250, 350, 500 GeV → 1 TeV*
  - Perform energy scans in-between, focus if we find something new

<table>
<thead>
<tr>
<th>$E_{\text{CM}}$ (GeV)</th>
<th>250</th>
<th>350</th>
<th>500</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity ($10^{34}$ cm$^{-2}$ s$^{-1}$)</td>
<td>0.75</td>
<td>1.0</td>
<td>1.8</td>
<td>4.9</td>
</tr>
<tr>
<td>Integrated Luminosity (fb$^{-1}$)</td>
<td>250</td>
<td>350</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>Number of days *</td>
<td>385</td>
<td>405</td>
<td>322</td>
<td>233</td>
</tr>
</tbody>
</table>

*assuming continuous operation at **peak luminosity**

**Luminosity** can be **doubled** by increasing the number of bunches per train (1300 → 2600)

Also expect improvement in **Damping Rings & Beam Delivery** in the future
The Higgs boson is a particle predicted by the Standard Model of particle physics that is responsible for giving mass to other particles. Its properties are of great interest due to the potential insights it can provide into the fundamental nature of matter.

### 2.4.1 Mass and Quantum Numbers

In the previous section, we discussed the capabilities of the LHC to measure the mass and quantum numbers of the Higgs boson. Now, let's explore the new probes of these quantities that the ILC offers, which are very attractive experimentally.

#### Precision

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>250 fb(^{-1})</th>
<th>1000 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_{ZH})</td>
<td>2.5%</td>
<td>1.2%</td>
</tr>
<tr>
<td>(g_{HZZ})</td>
<td>1.2%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

At 250 GeV:
- \(\sigma_{ZH}\) dominates

At 500 GeV:
- \(\Gamma^\text{tot}\) precision: <1%

\[ \Gamma^\text{tot} = \frac{\Gamma(H \rightarrow WW^*)}{BR(H \rightarrow WW^*)} \]
Can reconstruct the Higgs independently of its decay mode
Can see invisible Higgs decays

Can reconstruct $Z \rightarrow \ell\ell$

$$m_{\text{recoil}}^2 = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

Higgs mass resolution
$$\Delta m_H \leq 30 \text{ MeV}$$

<table>
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<tr>
<th>Precision</th>
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Model-independent absolute measurements
Higgs Branching Ratios

\[ m_H = 120 \text{ GeV} \]

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

\[ e^+e^- \rightarrow v\bar{v}H \]

\[ \sigma \cdot BR(H \rightarrow b\bar{b}) \]
\[ \sigma \cdot BR(H \rightarrow c\bar{c}) \]
\[ \sigma \cdot BR(H \rightarrow gg) \]
\[ \sigma \cdot BR(H \rightarrow WW^*) \]
\[ \sigma \cdot BR(H \rightarrow \tau^+\tau^-) \]
\[ \sigma \cdot BR(H \rightarrow ZZ^*) \]
\[ \sigma \cdot BR(H \rightarrow \gamma\gamma) \]

\[ \sigma_{ZH} (\sigma_{v\bar{v}H}) \text{ precision} \]
1.2-2.5% (2-3%)  

Yukawa coupling precision O(1%)
Top Yukawa Coupling

- Top Yukawa ≈ 1
  - Any special reason why the top is so heavy?

Strongly Interacting Light Higgs:
Top Yukawa may deviate 10's of % from SM value

Direct measurement challenging at LHC; $H \rightarrow \tau \tau$ may be possible

<table>
<thead>
<tr>
<th>Int. Lumi.</th>
<th>S/B</th>
<th>Efficiency</th>
<th>Cross section $\Delta \sigma/\sigma$</th>
<th>Top Yukawa $\Delta y/y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ab$^{-1}$</td>
<td>~0.4</td>
<td>~0.15</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>4 ab$^{-1}$</td>
<td>~0.4</td>
<td>~0.15</td>
<td>10%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Top Yukawa coupling: 5-10% precision (500 GeV)
Higher sensitivity at 1 TeV
Relationship between coupling and mass

→ Verify mass generation mechanism

→ Deviation is sign of new physics!
Sensitivity to New Physics Parameters

**Higgs-Singlet Mixing**
e.g. $U(1)_{B-L}$, Radion, Dilaton

\[ \Delta g_{hVV}^{\text{SM}} \approx -\sin^2 \theta_h / 2 \]

**Composite Higgs**
e.g. Little Higgs, Holographic Higgs

\[ \Delta g_{hVV}^{\text{SM}} \approx -c_H \xi / 2, \quad \xi = v^2 / f^2 \]

\[ \frac{\Delta g_{hbb}}{g_{hSM bb}} = \frac{\Delta g_{h\tau\tau}}{g_{hSM \tau\tau}} \approx 1.7\% \left( \frac{1 \text{ TeV}}{m_A} \right)^2 \]

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**MSSM**
\[ \tan \beta = 5, \text{ radiative corr.} \sim 1 \]

**Composite Scale** $f (\text{TeV})$

- $hZZ: 1\%$
- $\theta_h < 0.15 \text{ rad}$
- $f > 1$-$2 \text{ TeV}$

**MSSM Parameter** $m_A (\text{TeV})$

- $m_A > 1 \text{ TeV}$
- $(\tan \beta = 5)$
“Finger-printing” Models

Higgs Coupling Precision with ILC Full Program (Model-Independent Analysis)

Singlet Mixing

MSSM / Type II 2HDM

Composite Higgs

Electroweak Baryogenesis
Higgs self-coupling (1)

Three-point coupling $\rightarrow$ vacuum condensation
- Want to determine the shape of Higgs potential
- Cosmology connection
Extended Higgs sectors motivated by Electroweak Baryogenesis predict large anomaly in self-coupling

$\lambda < 2.5$
$\Lambda > 4 \text{ TeV}$

Kanemura, Shindou, Yagyu (2010)
Higgs self-coupling (2)

- **ZHH** cross section \( \sim 0.2 \text{ fb} \); main mode is **6 jets** (8 jets with one \( H \rightarrow WW \))
  - Current result only looks at \( H \rightarrow bb \) mode

<table>
<thead>
<tr>
<th>S/B</th>
<th>Efficiency</th>
<th>( \Delta \sigma/\sigma ) 2 ab(^{-1} )</th>
<th>( \Delta \sigma/\sigma ) 4 ab(^{-1} )</th>
<th>( \Delta \sigma/\sigma ) 8 ab(^{-1} )</th>
</tr>
</thead>
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<tr>
<td>~0.5</td>
<td>10%</td>
<td>30%</td>
<td>21%</td>
<td>15%</td>
</tr>
<tr>
<td>~0.75</td>
<td>15%</td>
<td>20%</td>
<td>14%</td>
<td>10%</td>
</tr>
<tr>
<td>~1.0</td>
<td>20%</td>
<td>15%</td>
<td>11%</td>
<td>7%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>S/B</th>
<th>Efficiency</th>
<th>( \Delta \lambda/\lambda ) 2 ab(^{-1} )</th>
<th>( \Delta \lambda/\lambda ) 4 ab(^{-1} )</th>
<th>( \Delta \lambda/\lambda ) 8 ab(^{-1} )</th>
</tr>
</thead>
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<tr>
<td>~0.5</td>
<td>10%</td>
<td>50%</td>
<td>35%</td>
<td>25%</td>
</tr>
<tr>
<td>~0.75</td>
<td>15%</td>
<td>33%</td>
<td>24%</td>
<td>17%</td>
</tr>
<tr>
<td>~1.0</td>
<td>20%</td>
<td>25%</td>
<td>18%</td>
<td>13%</td>
</tr>
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</table>

Future prospects: include \( H \rightarrow WW \), improve jet finders, b tagging

Measure possible **large anomaly** in self-coupling

Measure self-coupling to **10-20% precision**
Sensitivity increases at 1 TeV

\( m_H = 120 \text{ GeV} \)
ILC
Accelerator and Detector
ILC Accelerator R&D

SCRF Cavity Yields

Yields satisfying ILC specifications
April 2012: ~80% (world average) → TDR target: 90%

Main R&D for ILC accelerator nearing completion
ILC technology ready in 2013
ILC Detector R&D

- **Vertex Detector:** pixel detectors & low material budget
- **Time Projection Chamber:** high resolution & low material budget, MPGD readout
- **Calorimeters:** high granularity sensors, 5x5mm² (ECAL), 3x3cm² (HCAL)

<table>
<thead>
<tr>
<th>Sensor Size</th>
<th>ILC</th>
<th>ATLAS</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex</td>
<td>5x5 mm²</td>
<td>400x50 mm²</td>
<td>x800</td>
</tr>
<tr>
<td>Tracker</td>
<td>1x6 mm²</td>
<td>13 mm²</td>
<td>x2.2</td>
</tr>
<tr>
<td>ECAL</td>
<td>5x5 mm² (Si)</td>
<td>39x39 mm²</td>
<td>x61</td>
</tr>
</tbody>
</table>

**Particle Flow Algorithm**

Separate calorimeter clusters at particle level
- use *best* energy measurement for *each* particle.
- offers unprecedented *jet energy resolution*

**Charged Tracks → Tracker,**
**Photons → ECAL,** **Neutral Hadrons → HCAL**

Next phase: **construction → physics results**
Physics at the ILC

250~500 GeV
Higgs Factory
Observe vacuum condensation
Verify origin of mass
Multiple Higgs? (e.g. SUSY)
Discover new physics

250~ GeV
Top Factory
Why is it important?
Precision

Electroweak
Search
Search for
Colorful/Direct

350 GeV

Vacuum condensation
Higgs self-coupling 10-20%

Origin of mass
HZZ, HWW coupling < 1%
Branching ratio O(1%)

Multiple Higgs?
Look for patterns in new measurements

Discovering new physics
Sensitivity to NP parameters in Higgs sector > ~1 TeV
Conclusions

• ILC will fully uncover the Higgs sector

• ILC technology is ready in 2013

• Precision measurements possible with ILC detector
Extra Slides
Invisible Width

ILC RDR 2007

10% if BR(inv.)=5%

< 3% if BR(inv)=100%

FIGURE 2.3-19. The expected accuracy on the invisible decay rate as a function of the branching ratio at $\sqrt{s} = 350$ GeV with 500 fb$^{-1}$ data (full lines). The other lines indicate the individual contributions from the measurement of the invisible rate (dashed lines) and the total Higgs–strahlung cross section (dotted lines); the large dots are the result of the indirect method [7]; from Ref. [92].