Higgs Signals at the ILC

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The LHC Early Phase for the ILC
Fermilab
12 – 14 April 2007
Higgs Physics at the ILC: Implications of Early Results from LHC

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Questions

• What could be the impact of early LHC results on the choice of the ultimate ILC energy range and the ILC upgrade path? Could there be issues that would need to be implemented into the ILC machine and detectors design from the start?

Higgs: ILC priority benchmark for doing precision property measurements; a lot of thought already into it for machine & detector

• Could there be cases that would change the consensus about the physics case or an ILC with an energy of about 500 GeV?

• What are the prospects for LHC/ILC interplay based on early LHC data?
Overview

- Case 1: Detection of one state with properties that are compatible with those of a Higgs boson

  - ILC: precision measurement of properties
  - impact on machine energy, upgrade path
  - LHC/ILC interplay

Is it really a Higgs boson?
Is it really the SM Higgs boson?
Overview

- Case 1: Detection of one state with properties that are compatible with those of a Higgs boson
  - ILC: precision measurement of properties
  - impact on machine energy, upgrade path
  - LHC/ILC interplay e.g., Hey, it's light. Can we do enough with a lower-energy ILC?

- Case 2: No experimental evidence for a Higgs boson at the early stage of the LHC
  - Is actually there, but hard to detect at the LHC
  - LHC/ILC interplay Possible to observe it with ILC?
Overview

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  - e.g., Hey, it's light. Can we do enough with a lower-energy ILC?

- Case 2: No experimental evidence for a Higgs boson at the early stage of the LHC
  - Is actually there, but hard to detect at the LHC
  - LHC/ILC interplay
  - Possible to observe it with ILC?
  - Is really not there
  - impact on machine energy, upgrade path (e.g., GigaZ, and/or very high energy)
  - LHC/ILC interplay
Motherhood

**LHC:** $pp$ scattering at 14 TeV

Scattering process of proton constituents with energy up to several TeV, strongly interacting mass reach

- huge QCD backgrounds, low signal-to-background ratios

From G. Weiglein

**ILC:** $e^+e^-$ scattering at $\sim0.5$–1 TeV

Clean exp. environment: well-defined initial state, tunable energy, beam polarization, GigaZ, $gg, e\nu, e^-e^-$ options, ...

- rel. small backgrounds high-precision physics
- relatively low rates, energy limited
Higgs Production at ILC

- "Higgs"strahlung

- Fusion
If Standard Model Higgs:

SM Higgs
Mass
120 GeV

Include fusion
HZ only

Cross-Section (fb)

Ecm (GeV)

0 100 200 300 400 500

200 300 400 500

0

Beam polarization:
reduce multi-boson backg., & change relative fractions

• Fusion
• "Reach" mode

W\phantom{+}^+ \to Z^0 \to H^0 \to Z^0 \to H^0

Higgs Production at ILC

• "Higgs" strahlung
• Precision mode

W^+ \to Z^0 \to H^0 \to Z^0 \to H^0

W^- \to Z^0 \to H^0 \to Z^0 \to H^0

SM Higgs
Including fusion
HZ only

Ecm (GeV)

0 500 1000 1500

500 1000 1500

0

M_H = 120 GeV

160

180

200

140

160

180

SM Higgs

Including fusion

HZ only

Cross-Section (fb)
Higgs Production at ILC

- "Higgs"strahlung
- Precision mode

- Fusion
- "Reach" mode

- Copious production! 1000's to 10,000's of Higgstrahlung and $WW$-fusion events per year.

If Standard Model Higgs:

- **Higgs Production at ILC**
  - e$^+$ + e$^-$ → $H^0$
  - e$^+$ + W$^+$ → $H^0$
  - e$^-$ + W$^-$ → $H^0$

If Standard Model Higgs:

- **SM Higgs Mass**
  - 120 GeV

- **Cross-Section (fb)**
  - **Include fusion**
  - **HZ only**

- **Baseline**
  - **Scan**

- **GigaZ**

- **Upgrade**

- **SM Higgs**
  - Including fusion
  - HZ only

- **M_H = 120 GeV**

- **Ecm (GeV)**
  - 500 to 1500 GeV
Higgs Decay (SM-like)

- Branching ratios and cross sections give the couplings

Total width starts to be directly measurable

From Spira, HDECAY

~LEP2

Sweet Spot

Branching Fraction

$M_H$ [GeV]

$\bar{b}b$

$W^+W^-$

$W^*W$

$Z\bar{z}$

$t\bar{t}$

$W, Z$

$\square, g$

$h^0$

$\bar{f}$

$\bar{f}$
Measure its Properties

- **Mass** \( \mathcal{M} = M_h^2/\nu \) Consistent w/ EW constraints?

- Yukawa couplings: \( g_{f \bar{f} H} \square m_f \) ? \( Br's, \square \) (mass to fermions?)

- Mass to vector bosons: \( g_{V VH} \square M_V \) ? \( Br's, \square \) \( v = Z,W \)

- More than one Higgs? \( h_i \)

- Decays to other bosons: \( h_i \) \( Br's, \square \)

- Form of Higgs Potential, self-coupling, \( ZHH \)

Is it really a Higgs boson? Is it the SM Higgs boson? (ultimately, both LHC & ILC find mass to < 0.1%; to be useful, needs "match" of ILC \( m_{top} \) precision)

- Total Width (direct) or \( Br's, \square \) (indirect)

- Spin, parity, CP nature

  Threshold, Ang. dist.

  Time constraints: won't be able to include other options of ILC \( e \bar{e}, e \bar{e} \)
Measure its Properties

- **Mass**
  
  \[ M_{h}^{2} \, / \, v \]

  Consistent w/ EW constraints?

- **Yukawa couplings**:

  \[ g_{f_{f_{f}}H} \, m_{f} ? \]

  Some, (mass to fermions?) low prec.

- **Mass to vector bosons**:

  \[ g_{\nu \nu \nu H} \, M_{\nu} ? \]

  \( \nu = Z, W \)

  More than one Higgs?

  \[ h_{i} \quad \text{Z} \quad \text{Z} \]

  Fully generate mass of \( Z \)?

- **Decays to other bosons**:

  \[ h_{i} \quad \text{Z}, \text{g} \]

  Sensitive to new physics

- **Form of Higgs Potential**, self-coupling,

  \( ZHH \)

- **Is it really a Higgs boson?**

  (ultimately, both LHC & ILC find mass to < 0.1%; to be useful, needs "match" of ILC \( m_{top} \) precision)

- **Is it the SM Higgs boson?**

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LHC Gives Single State ...

If SM-like:

Possible:
- $H^\pm$ (more so with CMS)
- $qqH^\pm$ $qqWW$
- $HH$ $WW$
- $H^\pm$ $ZZ$ 4l

Likely
- $qqWW$
- $ttH, H^\pm$ $bb$
- $H^\pm$ $WW$ 4l
- Combined

Luminosity for 5

$\mathcal{L} \, dt = 10 \, fb^{-1}$

Possible:
- $H^\pm$ (partic. if SUSY $h$)
- $qqH^\pm$ $qqWW$
- $HH$ $WW$ 4l
- $H^\pm$ $ZZ$ 4l

Mass from

<1% to ~3%

(ZZ)
$M_h < 180 – 200 \text{ GeV?}$  LHC-ILC Interplay

- LHC does not measure absolute total production cross section, instead:

\[ \sigma(H) \times Br(H \rightarrow X) = \frac{\sigma(H)^{SM}}{\Gamma_{prod}^{SM}} \cdot \frac{\Gamma_{prod}}{\Gamma_{tot}} \cdot \frac{\Gamma_{decay}}{\Gamma_{tot}} \]

Narrow-width approximation

- Gives **combinations** of widths, couplings

  - $g_{HVV} < 1.05 \Gamma_{HVV}^{SM}$
  - Observe $H \rightarrow VV$ in weak vector boson fusion (WBF)

  Duhrssen et al., hep-ph/0407190

- Get absolute couplings
\( M_h < 180 - 200 \text{ GeV? LHC-ILC Interplay} \)

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\sigma(H) \times Br(H \rightarrow X) = \frac{\sigma(H)^{SM}}{\Gamma_{\text{prod}}^{SM}} \cdot \frac{\Gamma_{\text{prod}}}{\Gamma_{\text{tot}}} \Gamma_{\text{decay}}
\]

Narrow-width approximation

- Gives combinations of widths, couplings

- \( g_{HVV} < 1.05 \Gamma_{HVV}^{SM} \)

- Observe \( H \rightarrow VV \) in weak vector boson fusion (WBF)

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- Get absolute couplings

**Caveats**

- Valid only in weakly-interacting models
- What if WBF rate significantly above or below SM?
- Interesting physics in that 5%
- Gives uncertainties on $g_{HXX}^2$ (not on $g_{HXX}$)
- Note differences with and without systematic errors

Duhrssen et al., hep-ph/0407190
What do we want?

- Is it really a Higgs boson?
- Does it couple to mass?
- Single Higgs boson generating all of the mass?

Yukawa couplings:
- $u$-type vs. $d$-type ($t$ vs. $b$)
- Quark vs. lepton ($b$ vs. $\mu$)
- 2nd gen. vs. 3rd gen ($c$ vs. $t$)
Couplings at ILC

Recoil mass:

\[ m_{\text{recoil}}^2 = s - 2E_Z \sqrt{s} - M_Z^2 \]

Include bremsstrahlung and beamstrahlung effects

All decays to \( X \), find branching fractions to a few %

- More precision from
  \[ Z \rightarrow e^+ e^- \quad Z \rightarrow \mu^+ \mu^- \]

Possible implications of LHC single state on ILC energy:

- Cross section,
  \[ \frac{\sigma_{ZH}}{\sigma_{ZH}} = 3.5\% \]
  \[ \frac{g_{ZZH}}{g_{ZZH}} = 1.8\% \]

- Higgs observable up to mass of \( \sim 350 \text{ GeV} \) for 500 GeV machine
**Optimal Energy?**

- Spin (scalar)

If $m_h < 200$ GeV from LHC, and

$\sqrt{s} \sim 350$ GeV or just above threshold best for Br's, cross sections, couplings, etc.

(see also F. Richard, P. Bambade LAL 07-03)

why not just have the ILC be a low-energy "Higgs factory"?

- Capability to scan in energy part of baseline design

$m_h = 120$ GeV

20 fb$^{-1}$/point
**Optimal Energy?**

- **Spin (scalar)**

If $m_h < 200$ GeV from LHC, and

$\sqrt{s} \sim 350$ GeV or just above threshold best for Br's, cross sections, couplings, etc.

(see also F. Richard, P. Bambade LAL 07-03)

why not just have the ILC be a low-energy "Higgs factory"?

- **Because of the importance of:**
  - $tth$
  - Higgs self-coupling (Higgs potential)
  - Rare Br's

- **Capability to scan in energy part of baseline design**

Dova, Garcia-Abia, Lohmann; hep-ph/0302113

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

\[ 20 \text{ fb}^{-1}/\text{point} \]
**Coupling to top, $g_{ttH}$**

- **Heavy Higgs**

- **But if light, radiation off top**
- Marginal measurement at 500 GeV ILC, but by then, may have measurement of $\sigma \times Br$ due to $gg \to t\bar{t}H \to t\bar{t}b\bar{b}$, $ttW^+W^-$ at the LHC

Input precision Br's from 350–500 GeV ILC for these decays

Coupling to top, $g_{ttH}$

- ...and then move to precision measurement after energy upgrade:

$$\frac{\Delta g_{ttH}}{g_{ttH}} = 6 - 13\% \text{ for Higgs masses } 120 - 200 \text{ GeV}$$

(800 GeV ILC with 1000 fb$^{-1}$)
**Higgs Potential: Self-Coupling, \( \Box \)**

Is it condensating? (resulting in spontaneous symmetry breaking...)

- \( m_h < 200 \text{ GeV} \): no self-coupling from LHC

**Standard Model**

\[
V(\Box) = (|\Box|^2 - v^2)^2
\]

\[
\mathcal{L} = \Box v^2 H^2 + \Box v H^3 + \frac{1}{4} \Box H^3
\]

\[
\Box_{HHH} = 3 M_H^2 / M_Z^2
\]

(in units of \( \Box_0 = M_Z^2 / v \sim 33.8 \text{ GeV} \))
Higgs Potential: Self-Coupling, $H^0$

- $m_h < 140$ GeV: ILC with $Zhh$ at 500 GeV is better, $\Delta \Gamma/\Gamma < 20\%$
- $140 < m_h < 200$ GeV: ILC with $\nu\nu$ at 1-1.5 TeV
  Continue checks with more realistic simulations & backgrounds...
  (80% pol. baseline)!
  (e.g., Gay, Barklow, Rosca; Bangalore '06)
- Heavier Higgs? SLHC
  (but would need input from ILC: $g_{tth}, g_{WW}, \Delta \Gamma_{tot}$)

100% electron polarization!
Couplings from Rare Br's

- Crank it up for the fusion process:

\[
\begin{align*}
\text{SM Higgs} & \quad \text{Including fusion} \\
& \quad \text{HZ only}
\end{align*}
\]

- Similar for \( h \rightarrow b\bar{b} \) (rare, i.e., \( Br \sim 0.2\% \) at \( m_h = 200 \text{ GeV} \))

- ...and \( h \rightarrow \gamma\gamma \)

Battaglia, de Roeck, hep-ph/0111307

Test universality: \( g_{t\tau h}/g_{b\bar{b}h} = 0.16 \),
800 GeV, 1000 fb\(^{-1}\)

Desch (hep-ph/0311092)
Combine Information

With theory assumptions:

Model Independent:

- Gives uncertainties on $g_{HXX}^2$ (not on $g_{HXX}$)
Precision needed on Couplings?

With theory assumptions

LHC alone: $2 \times 300 \text{ fb}^{-1}$

- e.g., single state, $m_h = 130 \text{ GeV}$
Precision needed on Couplings?

Model Independent

- e.g., single state, $m_h = 130$ GeV

Adapted from S. Yamashita
Systematics

- All these precision results rely intimately on:
  - Jet finding / jet clustering
  - Jet energy calculation (particle flow)
  - $b$, $c$, top, $t$ tagging
  - $W$, $Z$ tagging
  - Kinematic constraint fits

and now with full GEANT simulation, with full or close-to-full software reconstruction - huge amount of work! (particularly if detector designs are still in development)

Example: impact of silicon sensor thickness on charm branching fraction

- particularly for multijet low-stats $tth$, self-coupling particularly for the Br "sweet spot", $m_h < 180$ GeV
Precision needed on Couplings?

Model Independent \( LHC \oplus ILC \)

- e.g., single state, \( m_h = 130 \text{ GeV} \)
- With possibility of observation of \( H^\pm \); other SUSY particles at LHC
**Precision needed on Couplings?**

Adapted from S. Yamashita

**Model Independent**

Electroweak Baryogenesis

- LHC
- ILC

Deviation from SM Value

- e.g., single state, $m_h = 130$ GeV
- e.g., single state, $m_h = 130$ GeV

and nifty interplay case where that LHC single state may not be a Higgs
Models with 3-branes in extra-dimensions predict a radion, \( f \), can mix with the Higgs.

Modified Higgs properties may be difficult to detect at the LHC.

That early LHC single state could be a radion, and not seeing the Higgs (swamped by background)

\[
    gg \rightarrow \phi \rightarrow ZZ^* \rightarrow 4\ell
\]

ILC guarantees observation of both Higgs & radion

\[
e^+e^- \rightarrow Zh, Z\phi
\]

over full parameter space, and precision measurements can determine the mixing.

LHC can see heavy Kaluza-Klein excitations.
• Single Higgs-like state at LHC?

Could be in a region where both LHC and ILC will see only the single lightest Higgs (although LHC could potentially observe decays into sparticles with ILC input)

\[ H \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \]

"The Wedge"
- Precision ILC measurement of

\[
r = \frac{[\text{Br}(h \rightarrow b\bar{b})/\text{Br}(h \rightarrow WW^*)]_{\text{MSSM}}}{[\text{Br}(h \rightarrow b\bar{b})/\text{Br}(h \rightarrow WW^*)]_{\text{SM}}}
\]

- Combine LHC and ILC info on SUSY spectrum (this case, SPS1a)

- No implications on initial energy for ILC (for Br's), but could give feedback on subsequent upgrade path
Single LHC State with $M_h > 200$ GeV?

- Far fewer fermion couplings now accessible!
- Still look for them though!
- $g_{ZZh}$, $g_{WWh}$ still determined to 2 – 9% for $200 < m < 320$ GeV with 500 fb$^{-1}$ at a 500 GeV ILC
- If $m_h > 350$ GeV skip initial ILC run at 500 GeV?
- Spin, other quantum numbers?
- Demand detector requirements not thought of? ("standard" is the $W/Z$ mass separation)

Single LHC State with $M_h > 200$ GeV?

- If $m_h > 2m_{\text{top}}$ then $h \rightarrow t\bar{t}$
  (tough at LHC, more interplay w/ ILC)
  $g_{tth}$ to better than 10% for $m_h < 650$ GeV

- What about the range $200$ GeV $< m_h < 2m_{\text{top}}$?

- How to get at other couplings?

- How far can the ILC realistically go in Higgs mass for measuring self-coupling? Will this determine the "top-end" of the upgrade path?

Clearly a lot to be looked into...
Single LHC State with $M_h > 200$ GeV?

- What if really heavy?
  - $500$ GeV < $m_h$ < $1$ TeV?
    - source of extra contributions in EW precision measurements may be obscure
    - GigaZ and scanning $WW$ threshold

Tension between running at highest energies and still being able to go down to lowest energies

<table>
<thead>
<tr>
<th>LHC</th>
<th>ILC</th>
</tr>
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<tbody>
<tr>
<td>Observes Heavy Higgs</td>
<td>Out of kinematic range</td>
</tr>
<tr>
<td>Non-standard decays of light Higgs; swamped by background</td>
<td>Observes light Higgs regardless of decay</td>
</tr>
</tbody>
</table>
No evidence of Higgs at early stage LHC

- Is actually there, but difficult/impossible to detect at the LHC

Recoil mass:

\[ m_{\text{recoil}}^2 = s - 2E_Z \sqrt{s} - M_{\ell\ell}^2 \]

- Any new scalar coupling to Z can be found via recoil method
  \[ e^+e^- \rightarrow Zh \] regardless of decay
  (also new scalars from Little Higgs, etc.)

In general, method better at lower energy ILC

Identify peak(s) in recoil mass, look for all decays: invisible, light jets, gluons, SUSY, even if overlapping
No evidence of Higgs at early stage LHC

Possibly a more relevant question:

Are $WW$ interactions perturbative up to the TeV scale?

Yes  ➔  Higgs-like state must be there
      ➔  ILC can see the state(s) that is regulating the bad energy behavior  Initial energy 500 GeV ILC fine

No  ➔  New physics involved, some strong interactions
      ➔  How are precision EW measurements being compensated?  Back to tension between possibly running ILC at higher initial energies but wanting EW precision from GigaZ and WW scans

Soooo, how soon can we know if $WW$ interactions remaining perturbative at the LHC?
No evidence of Higgs at early stage LHC

- Is actually there, but difficult/impossible to detect at the LHC

Just a few examples:

- $h \rightarrow \text{jets}$ of no particular flavor content; in MSSM with very light $\widetilde{b}$ with $R$-parity violating decays evading LEP limits
  
  If $Br(h \rightarrow \text{jets}) \approx (2 - 5) \times Br(h \rightarrow b\bar{b})$ difficult to observe at LHC; no problem at initial energy ILC

- MSSM with light stop quarks suppressing $ggh$ coupling, reducing standard gluon-fusion discovery modes at LHC or enhanced branching fraction $Br(h \rightarrow \chi_{1}^{0}\chi_{1}^{0})$
  
  (LHC can detect invisible Br's up to $\sim 0.25$–$0.30$); no problem at initial energy ILC


e.g., Boudjema, Belanger, Godbole; hep-ph/0206311
No evidence of Higgs at early stage LHC

- Is actually there, but difficult/impossible to detect at the LHC

Just a few examples:

- NMSSM models, add Higgs singlet, get additional scalar (three CP-even states) and pseudoscalar

  \[ h_i \rightarrow a_1a_1 \quad \text{CP even} \quad a \rightarrow b\bar{b} \quad \text{Very light CP-odds} \quad a \rightarrow \tau^+\tau^- \]

  LHC: \[ WW \rightarrow h_i \rightarrow aa \quad , \text{4-}b \text{ state swamped by background} \]

  ILC: \[ e^+e^- \rightarrow Zh \rightarrow Zaa \rightarrow Zb\bar{bb}, b\bar{b}\tau^+\tau^- \]

  Detect both in recoil method

  Check if \( Br(a \rightarrow \tau^+\tau^-)/Br(a \rightarrow b\bar{b}) \) consistent with CP-odd scalar

  No problem at initial energy ILC

  No change in energy strategy; no significant additional detector capabilities (beyond strict control of systematics for couplings)
No evidence of Higgs at early stage LHC

- Is really not there
- Strongly-interacting sector or a mix of strong and weak interactions
- Look at 6-fermion processes at LHC & ILC, anomalous gauge couplings
- Resonances at high energy (LHC, measure masses)
- If beyond reach of LHC, indirect sensitivity at ILC to very heavy resonances (think Tristan and the Z...)
- If within reach of LC, measure the couplings in detail (particularly with polarized beams)

Impossible to tell early on, but could eventually lead to possibly running ILC at higher initial energies but wanting EW precision from GigaZ and WW scans
Summary

At the early stages of LHC:

- Case 1: Detection of one state with properties that are compatible with those of a Higgs boson
  
  \[ m_h < 200 \text{ GeV} \]
  
  Initial energy of 500 GeV and upgrade path to 1 TeV justified; need higher energies for complete couplings

  \[ m_h > 200 \text{ GeV} \]
  
  Most uncertainty, much depends on what is observed outside the Higgs sector (e.g., GigaZ and higher energy as \( m_h \uparrow \))

- Case 2: No experimental evidence for a Higgs boson at the early stage of the LHC

  Will be too early to tell if:
  
  Is actually there, but hard to detect at the LHC
  or
  Is really not there

- LHC-ILC interplay everywhere

- More complete simulations needed to verify precision performance
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  *Toward High Precision Higgs-Boson Measurements at the ILC*, hep-ph/0511332, Snowmass '05 Report