Higgs and Electroweak Symmetry Breaking

*Experimental Aspects*

Tim Barklow
SLAC
LCWS 04, April 23, 2004
More Complete Picture of LC Capabilities is Emerging Through More Detailed Analyses:

- Beam Related Sys Errors in Higgs Mass Measurements
- Comprehensive Jet Flavor Tagging Analysis for $\text{BR}(h \rightarrow bb, cc, gg)$
- Overlaid Events, Vertex Smearing & Crab Crossing in $\gamma\gamma \rightarrow h \rightarrow bb$
- LHC/LC Complementarity:
  - $M_A$ Determination From Higgs Branching Ratios
  - Study of MSSM Higgs Bosons in the Intense-Coupling Regime
- New Results From Analyses at $E_{cm}=1\text{TeV}$:
  - Branching Fractions for Rare Higgs Decays
  - Improved Higgs Self Coupling Measurement
Beam Related Systematics in Higgs Mass Measurement

Alexei Raspereza

LC Workshop, Paris 20/4/2004
Differential Luminosity Spectrum

- Beamstrahlung $\rightarrow$ distortion of beam energy spectrum
- Parametrization:
  \[ f(x) = a_0 \delta(1-x) + a_1 x a_2 (1-x) a_3, \quad x = \frac{E_e}{E_{\text{beam}}} \]
- \( f(x)\,dx = 1 \rightarrow 3 \) independent parameters: \( a_0, a_2, a_3 \)
- acollinearity spectrum in Bhabha events $\rightarrow$ differential luminosity spectrum measurement
- K. Moenig, LC-PHSM-2000-60: \( \delta a_i / a_i \leq 1\% \) with 3 \( \text{fb}^{-1} \) @ \( \sqrt{s} = 500 \text{ GeV} \)

\( \sqrt{s} = 350 \text{ GeV} : a_0 = 0.55, \quad a_1 = 0.59, \quad a_2 = 20.3, \quad a_3 = -0.63 \)
Differential Luminosity Spectrum

$\delta a_i \sim 10\% : \text{effect O(10MeV) on Higgs mass}$

$\delta a_i \leq 1\% : \text{effect of O(MeV) on Higgs mass}$
Simdet Detector Simulation of $e^+e^- \rightarrow Zh$

$Z \rightarrow e^+e^-, \mu^+\mu^-$

$\sqrt{s} = 350 GeV \ L = 500 \ fb^{-1}$

Recoil Mass Results:

\[ \frac{\delta E_e}{E_e} = 0.3\% \]

NLC

\[ \delta M_h = 143 MeV \]

\[ \frac{\delta E_e}{E_e} = 0.1\% \]

TESLA

\[ \delta M_h = 117 MeV \]

Recoil mass energy scale error : \( \delta M_h = 2.9 \delta E_e \)
**M_H measurement using kinematic fit of qqll and qqqb**

**Energy scale error**

\[ \delta M_h = 1.0 \delta E_e \quad (qqll) \]
\[ \delta M_h = 0.8 \delta E_e \quad (qqqq) \]

\[ \delta E_{e^+} = \delta E_{e^-} = \pm 25 \text{ MeV} \] results in a mass shift
\[ \sim 25 \text{ MeV for } HZ \quad qqll \]
\[ \sim 20 \text{ MeV for } HZ \quad qqqq \]

**Effect of beam spread**
- statistical accuracy degrades
  - from 45 to 50 MeV in HZ → qqqq channel
  - from 70 to 80 MeV in HZ → qqll channel
  - if one assumes 0.5% beam spread for both e^+ and e^-
  \[ \Rightarrow \] statistical accuracy degrades
- from 72 to 76 MeV (6\%) for TESLA → NLC (qqll)
- from 46 to 48 MeV (4\%) for TESLA → NLC (qqqq)
<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\delta E/E=0$</th>
<th>$\delta E/E=0.1%$</th>
<th>$\delta E/E=0.3%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>recoil mass</td>
<td>110</td>
<td>117</td>
<td>143</td>
</tr>
<tr>
<td>$ZH \rightarrow l^+l^-q\bar{q}$</td>
<td>70</td>
<td>72</td>
<td>76</td>
</tr>
<tr>
<td>$ZH \rightarrow q\bar{q}b\bar{b}$</td>
<td>45</td>
<td>46</td>
<td>48</td>
</tr>
<tr>
<td>Combined</td>
<td>38</td>
<td>39</td>
<td>40</td>
</tr>
</tbody>
</table>

$\delta M_h$ in MeV

MSSM theory error on $m_h$: (S. Heinemeyer)

Current theory uncertainty: $\delta m_h^{\text{theo,today}} \approx 3$ GeV

Future theory uncertainty: $\delta m_h^{\text{theo,future}} \lesssim 0.5$ GeV necessary/possible

Future parametric uncertainty: $\delta m_h^{\text{para,future}} = \mathcal{O}(0.2 \text{ GeV})$ ($m_t, \alpha_s$)
Flavor Tag

**Vertex reconstruction:** ZVTOP (from SLD)
- Tracks interpreted as probability tubes
- Vertex: crossings of these tubes

**Neural Net** for Flavor-separation
- Training: HZ → qql events at 350 GeV
- Most important input variable: vertex mass

Thorsten Kuhl  20.04.2004, LCWS Paris
Neural Net performance

Comparison of fast Simdet and full Brahms simulation

- Simdet tuned with this Brahms version (91.2 GeV)
- C-Tag: Very good agreement
- B-Tag: Reasonable, differences: missing resolution tails

Vertex Detector dependence:

- Two jet tag for Higgs events at 350 GeV (net used for this analysis!)
- With/without innermost layer
- B-Tag: Very robust
- C-Tag: Very sensitive benchmark
Results

- **Combined result** (all 3 channels, $m_H = 120$ GeV, ECM=350 GeV, 500fb$^{-1}$):
  - $\Delta(\sigma \text{ BR}(H\rightarrow bb)/\sigma_{\text{SM}})$: $68.20\pm 0.75\%$
  - $\Delta(\sigma \text{ BR}(H\rightarrow cc)/\sigma_{\text{SM}})$: $3.01 \pm 0.36\%$
  - $\Delta(\sigma \text{ BR}(H\rightarrow gg)/\sigma_{\text{SM}})$: $6.70 \pm 0.55\%$

- **Individual channels:**

<table>
<thead>
<tr>
<th></th>
<th>$Z\rightarrow\text{all}$</th>
<th>$Z\rightarrow qq$</th>
<th>$Z\rightarrow ll$</th>
<th>$Z\rightarrow\nu\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta(\sigma \text{ BR})/\sigma \text{ BR}(bb)$</td>
<td>1.1%</td>
<td>1.5%</td>
<td>3.0%</td>
<td>2.1%</td>
</tr>
<tr>
<td>$\Delta(\sigma \text{ BR})/\sigma \text{ BR}(cc)$</td>
<td>12.1%</td>
<td>17.5%</td>
<td>33.0%</td>
<td>20.5%</td>
</tr>
<tr>
<td>$\Delta(\sigma \text{ BR})/\sigma \text{ BR}(gg)$</td>
<td>8.3%</td>
<td>14.4%</td>
<td>18.5%</td>
<td>12.3%</td>
</tr>
</tbody>
</table>

- Error checked with 10 independent samples: no bias observed
- Different background composition of different selection channels is helpful
- Missing: Correct treatment of other Higgs decay channels (WW, $\tau\tau$, ZZ), currently treaten as fixed background
### Comparison

<table>
<thead>
<tr>
<th></th>
<th>$\Delta(\sigma BR)/(\sigma BR)(bb)$</th>
<th>$\Delta(\sigma BR)/(\sigma BR)(cc)$</th>
<th>$\Delta(\sigma BR)/(\sigma BR)(gg)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>This analysis</td>
<td>1.1%</td>
<td>12.1%</td>
<td>8.3%</td>
</tr>
<tr>
<td>TDR (Battaglia) *</td>
<td>0.9%</td>
<td>8.0%</td>
<td>5.1%</td>
</tr>
<tr>
<td>Snowmass (Brau, Potter)</td>
<td>1.6%</td>
<td>19.0%</td>
<td>10.4%</td>
</tr>
</tbody>
</table>

*For comparison: Subtracting 2.2% error on total Higgs cross section to get ??? and use standard model fraction of fusion channel

- **TDR analysis (Marco Battaglia):**
  - Error for cc and gg 50% larger
  - New selection more efficient in qqvv and qqll
  - Difference: rather optimistic flavor-tag parame

- **Snowmass analysis (Brau/Potter):**
  - Flavor tagging of American LC-group is a bit better (innermost layer at 1.2 cm)
  - Differences:
    - More fancy analysis (used not all channels)
    - Cuts for flavor separation instead of 2-dim. Fit
Improved analysis on $\gamma\gamma \rightarrow higgs \rightarrow b\bar{b}$ including overlaid events, vertex smearing and crab crossing for SM and MSSM

P. Nieżurawski, A. F. Żarnecki, M. Krawczyk

Faculty of Physics
Warsaw University
Our analysis of precision $\sigma(\gamma\gamma \rightarrow higgs \rightarrow b\bar{b})$ measurement includes:

- realistic $\gamma\gamma$-spectra

- $b$-tagging

- overlaying events $\gamma\gamma \rightarrow$ hadrons (OE)

- results for SM at $M_h = 120, 130, 140, 150, 160$ GeV

- results for MSSM at $M_A = 200, 250, 300, 350$ GeV with $\tan\beta = 7$, $M_2 = \mu = 200$ GeV (following M. Mühlleitner et al.)

Recent development:

- crossing angle

- primary vertex distribution
Crab-wise crossing of beams

\[ \sigma'_x = \sqrt{\frac{1}{2} (\sigma_x^2 + \sigma_z^2 \tan^2 (\alpha_c/2))} \quad \sigma'_y = \frac{\sigma_y}{\sqrt{2}} \quad \sigma'_z = \frac{\sigma_z}{\sqrt{2}} \]

Bunch:
- \( \sigma_x = 140 \text{ nm} \)
- \( \sigma_y = 7 \text{ nm} \)
- \( \sigma_z = 0.3 \text{ mm} \)

Primary vertex:
- \( \sigma'_x = 3.6 \mu\text{m} \)
- \( \sigma'_y = 5 \text{ nm} \)
- \( \sigma'_z = 0.2 \text{ mm} \)

\( \alpha_c = 34 \text{ mrad} \)
SM summary, $M_h = 120-160$ GeV

NŻK

- with OE, primary vtx distrib.
- with OE
- without OE

$\Delta \sigma/\sigma$ for $\gamma+\gamma \rightarrow h \rightarrow b\bar{b}$ [%]

$M_h$ [GeV]

115 120 125 130 135 140 145 150 155 160 165
MSSM, $M_A = 200-350$ GeV

NŽK

$tg\beta=7$  $M_2=\mu=200$ GeV

- with OE, primary vtx distrib.
- with OE
- without OE

$\Delta\sigma/\sigma$ for $\gamma\gamma\rightarrow A,H \rightarrow bb$

$M_A$ [GeV]

0  200  220  240  260  280  300  320  340  360
$M_A$ determination from the Higgs branching ratios with full parametric uncertainties
Indirect constrains on $M_A$

- Several analyses have been performed:

- They all kept fixed all parameters except one under investigation (i.e. $M_A$) assuming that SUSY parameters enter without any experimental or theoretical uncertainty $\Rightarrow$ here we take into account all experimental and theoretical uncertainties.
Indirect constrains on $M_A$

- Model is SPS1a with following errors assumed:

<table>
<thead>
<tr>
<th>$\Delta m_{sb1}$</th>
<th>$\Delta m_{sb2}$</th>
<th>$\Delta m_{\text{gluino}}$</th>
<th>$\Delta m_{st1}$</th>
<th>$\Delta m_h$</th>
<th>$\tan\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.7 GeV</td>
<td>6.2 GeV</td>
<td>6.5 GeV</td>
<td>2 GeV</td>
<td>0.5 GeV</td>
<td>10%</td>
</tr>
</tbody>
</table>

- We assume that we can measure lighter stop at LC, $m \sim 400$ GeV

- Precise measurement of $m_h$ with an error from theory included

- We compare theoretical prediction of

\[ r = \frac{\left[ BR(h \rightarrow bb) / BR(h \rightarrow WW^*) \right]_{MSSM}}{\left[ BR(h \rightarrow bb) / BR(h \rightarrow WW^*) \right]_{SM}} \]

with its prospective experimental measurements

- Even though the experimental error of the two BR’s is larger than that of the individual ones, it has stronger sensitivity

18/04/2004

L. Živković
Conclusions

- If we find just one Higgs boson at LHC, precision measurement at LC would allow to tell its nature (SM or MSSM)

- We could put constraints on the mass of the CP-odd Higgs boson precision would be 20 (30)% for $m_A$ equal to 600 (800) GeV

- If we find several Higgs bosons at LHC, precision measurement at LC would allow us to shed some light on the possible model
Search for the MSSM Higgses in the intense-coupling regime at a Linear Collider (TESLA)

Edward Boos

At least the lightest Higgs boson $h$ must have a mass below some value of $130 - 135$ GeV.

In the decoupling regime $H, A$ and $H^\pm$ are heavy $M_A \sim M_H \sim M_{H^\pm}$

The lightest Higgs particle $h$ is similar to the SM Higgs

Another, more complex, situation is when pseudoscalar $A$ boson is not much larger than $h$, and $\tan \beta$ is large.

Masses could be rather close.

Widths are large.

Couplings and Br-fractions in some cases are significantly different from SM or decoupling regime.

So, the phenomenology is different.

Such a scenario was called the Intense-coupling regime

(E.B., A.Djouadi, M.Mühlleitner, A.Vologdin)
Total Width and Branching Fractions

Graphs showing the total width and branching fractions for different particles, with axes labeled for mass and BR (branching ratio) values.
How to resolve?

At the LHC:
\( \text{Br}(h, H, A \rightarrow \gamma \gamma) \sim 10^{-5} - 10^{-6} - \text{too small} \)
\( \bar{b}b \) and \( \tau^+ \tau^- \) modes - energy resolution is not enough
More promising - \( \mu^+ \mu^- \) Higgs decay in \( \bar{b}b + h, H, A \) production:
\( \text{Br}(h, H, A \rightarrow \mu^+ \mu^-) \sim 3 - 3.5 \times 10^{-4} \), Energy resolution for muons 
\( \sim 1 - 1.5 \ \text{GeV} \), Tagging b-jets

At LC a multichannel analysis should be used:
1. \( \bar{b}b l^+ l^- \) mode using recoil mass for the Higgsstrahlung
2. \( \bar{b}b \bar{b}b \) and/or \( \bar{b}b \tau^+ \tau^- \) modes for the Higgs pair production

Conclusions

- The intense coupling regime - one of the most difficult scenario to be resolved completely
  (At the LHC - one can separate states if mass differences are about 5 GeV or more)

- At LC - \( h \) and \( H \) masses could be measured to about 80-280 MeV accuracy at 
  energies about 300 GeV and 500 \( fb^{-1} \) lumi in the 2 leptons + 2 b-jets mode using 
  the recoil mass technique

- Mass of the A Higgs bosons can be measured to a similar accuracy in the 4 b-jet 
  mode (Ah+AH) using measured values \( M_h \) and \( M_H \) and applying the 
  ”combinatorial mass difference” analysis
Higgs Coupling Measurements at 1 TeV (T. Barklow)

Take cue from Battaglia & DeRoeck results for $B_{h \to \mu \mu}$ at CLIC and investigate branching fraction measurements in WW fusion at a 1 TeV LC.

\[ e_{pol}^- = -80\% \quad L = 500 \ (1000) \ \text{fb}^{-1} \quad \text{for} \quad \sqrt{s} = 350 \ (1000) \ \text{GeV} : \]

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>$e_{pol}^+$ (%)</th>
<th>120</th>
<th>140</th>
<th>160</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>0</td>
<td>110280</td>
<td>89150</td>
<td>69975</td>
<td>37385</td>
</tr>
<tr>
<td>350</td>
<td>+50</td>
<td>159115</td>
<td>128520</td>
<td>100800</td>
<td>53775</td>
</tr>
<tr>
<td>1000</td>
<td>0</td>
<td>386550</td>
<td>350690</td>
<td>317530</td>
<td>259190</td>
</tr>
<tr>
<td>1000</td>
<td>+50</td>
<td>569750</td>
<td>516830</td>
<td>467900</td>
<td>382070</td>
</tr>
</tbody>
</table>

Results presented for $h \to b\bar{b}, W^+W^-, gg, \gamma\gamma, ZZ$

No results for $h \to c\bar{c}, \tau^+\tau^-$ since detailed charm-tagging beyond scope and Higgs mass resolution for $h \to \tau^+\tau^-$ severely degraded by neutrinos.
$M_h = 200 \text{ GeV}$

$\sqrt{s} = 1 \text{ TeV}$

$L = 1 \text{ ab}^{-1}$

All 2,4,6-fermion and top-resonance 8-fermion backgrounds included.

Background passing cuts (white histogram) is mostly

$e^+e^- \rightarrow e^+e^-W^+W^-$

Red histogram: $h \rightarrow b\bar{b}$

Green histogram: $h \rightarrow WW, ZZ$

$\Delta B_{bb} / B_{bb} = 0.09$
$M_h = 120 \text{ GeV}$

$\sqrt{s} = 1 \text{ TeV}$

$L = 1 \text{ ab}^{-1}$

All 2,4,6-fermion and top-resonance 8-fermion backgrounds included

Non-Higgs background (white histogram) is mostly

$e^+ e^- \rightarrow \nu e \nu e h$

Red histogram: $h \rightarrow \gamma \gamma$

$\Delta B_{\gamma\gamma} / B_{\gamma\gamma} = 0.05$
<table>
<thead>
<tr>
<th>Channel</th>
<th>( M_H = 120 \text{ GeV} )</th>
<th>( M_H = 140 \text{ GeV} )</th>
<th>( M_H = 160 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H^0/h^0 \to bb )</td>
<td>± 0.024</td>
<td>± 0.026</td>
<td>± 0.065</td>
</tr>
<tr>
<td>( H^0/h^0 \to c\bar{c} )</td>
<td>± 0.083</td>
<td>± 0.190</td>
<td></td>
</tr>
<tr>
<td>( H^0/h^0 \to gg )</td>
<td>± 0.055</td>
<td>± 0.140</td>
<td></td>
</tr>
<tr>
<td>( H^0/h^0 \to \tau^+\tau^- )</td>
<td>± 0.050</td>
<td>± 0.080</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \Gamma_{H\to X} )</th>
<th>( \text{BR}(H \to X) )</th>
<th>( M_H = 120 \text{ GeV} )</th>
<th>140 GeV</th>
<th>160 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( WW = WW_{\nu\nu} )</td>
<td>( H^0 \to WW )</td>
<td>±0.061</td>
<td>±0.045</td>
<td>±0.134</td>
</tr>
</tbody>
</table>

1 TeV ANALYSIS:

<table>
<thead>
<tr>
<th>( \Delta B_{bb}/B_{bb} )</th>
<th>( \Delta B_{WW}/B_{WW} )</th>
<th>( \Delta B_{gg}/B_{gg} )</th>
<th>( \Delta B_{\gamma\gamma}/B_{\gamma\gamma} )</th>
<th>( \Delta \Gamma_{tot}/\Gamma_{tot} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>±0.015</td>
<td>±0.016</td>
<td>±0.018</td>
<td>±0.020</td>
<td>±0.090</td>
</tr>
<tr>
<td>±0.024</td>
<td>±0.020</td>
<td>±0.018</td>
<td>±0.010</td>
<td>±0.025</td>
</tr>
<tr>
<td>±0.021</td>
<td>±0.023</td>
<td>±0.035</td>
<td>±0.146</td>
<td></td>
</tr>
<tr>
<td>±0.055</td>
<td>±0.054</td>
<td>±0.062</td>
<td>±0.237</td>
<td></td>
</tr>
<tr>
<td>±0.035</td>
<td>±0.034</td>
<td>±0.036</td>
<td>±0.020</td>
<td>±0.050</td>
</tr>
</tbody>
</table>
A study of Higgs self-coupling measurement at about 1 TeV

ICEPP, Univ. of Tokyo
S. Yamashita

@1TeV  2 main modes

\[ e^+e^- \rightarrow ZHH \]
\[ e^+e^- \rightarrow (W^+W^-)\nu\bar{\nu} \rightarrow HH\nu\bar{\nu} \]

etc..

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Graph showing total cross section vs. root(s) [GeV] for the processes:

- Zhh
- W-fusion
- Combined

Y. Yasui et al

solid: \( m_h = 120 \text{ GeV} \)
dashed: \( m_h = 180 \text{ GeV} \)
**Likelihood selection**
(~ OPAL Higgs scheme)

Using:
Compatibility to $\nu\nu hh$ $\nu\nu ZZ$ $\nu\nu Zh$ etc..

**After Likelihood selection**

Separate ‘$Zhh$’ & ‘fusion-channel’

---

**$\nu\nu hh$ selection**

$L = 1 \text{ ab}^{-1}$

$\Lambda = 0$

$\nu\nu hh$

$\Lambda = \Lambda_{SM}$

---

**$\nu\nu hh$ channel**

`fusion`

`$Zhh$`

---

04.4.20

satoru@icepp.s.u-tokyo.ac.jp
\( \Lambda \) measurement sensitivity

- Fusion channel
- Zhh channel
- Combined

\[ \Lambda = \Lambda_{\text{SM}} \]

\[ I_{\text{lumi}} = 1 \text{ ab}^{-1} \]

\[ P_{\text{Pol}} = -80\% \]

@ 1 TeV

\( \Lambda / \Lambda_{\text{SM}} \)

0.4

1.6
A quick simulation study has been performed for $E_{cm} = 1$ TeV under the condition:
- $\delta E_{jet}/E_{jet} \sim 30\%/\sqrt{E_{jet}}$(GeV)
- 4b tag efficiency $\sim 80\%$, eff for non-4b $< a$ few %
- $I_{lumi}=1$ ab$^{-1}$ e beam Pol $\sim -80\%$

only $hh \rightarrow bbbb$ decay mode (Br(hh$\rightarrow$bbbb)$\sim$47%) analyzed.

Likelihood selection $\rightarrow$ overall signal eff $\sim 32\%$ for $vvh$ $\sim 22\%$ for $Zhh$ ($Z \rightarrow qq, t\bar{t}t$)

For $M_h=120$ GeV: A measurement sensitivity (only $hh \rightarrow bbbb$ only)

<table>
<thead>
<tr>
<th>$\Lambda = \Lambda_{SM}$</th>
<th>$\Lambda/\Lambda_{SM}$</th>
<th>$0.78 - 1.32$ (95%CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda/\Lambda_{SM}=0.6$</td>
<td>0.6 $+0.10 -0.07$ (1$\sigma$)</td>
<td>$0.45 - 0.77$ (95%CL)</td>
</tr>
<tr>
<td>$\Lambda/\Lambda_{SM}=1.4$</td>
<td>1.4 $+0.14 -0.18$ (1$\sigma$)</td>
<td>$1.08 - 1.70$ (95%CL)</td>
</tr>
</tbody>
</table>

Analysis is premature, and can increase the sensitivity. - e.g. when non-b decay of Higgs is included (especially important for $M_t > 130$ GeV)

Relative phase (and sign) of $\Lambda$ can be measured using interference comparing results from $Zhh$ and fusion processes, or results of different $E_{cm}$’s.

At Jeju LCWS 2002 result was $\delta \Lambda/\Lambda = 0.20$ for 2ab$^{-1}$ at $E_{cm} = 500$ GeV
Summary Higgs Experimental
LCWS 2004

• Beam related systematic errors have been evaluated for the Higgs mass measurement.
• Jet flavor tagging efficiency, purity for Higgs decays appears to be understood.
• Very detailed systematic error study has been performed for $\gamma\gamma \rightarrow h \rightarrow bb$ and no problems found.
• Nice examples of LHC/LC complementarity found in Higgs physics.
• $E_{cm}=1\text{TeV}$ can be used to probe rare Higgs decays and measure Higgs self-coupling to 10%.