Higgs Physics at Higgs Factories

Status of Higgs property measurements
Cases for a Higgs factory
Hadron and lepton collision differences
Expected precisions at ee Higgs factories

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University of Michigan

Conference on the Future of High Energy Physics
Hong Kong, China, January 19-22, 2015
Circumference and Energy...

88 TeV

in a 88 km tunnel

Great public outreach,
every Chinese understands this...

.... the 2008 Beijing Olympics opened at 8:08pm on August 8!
Related Talks

**Today:**

Frank Simon - Physics at Linear Colliders

Aleandro Nisati - Higgs Prospects at HL-LHC

Liantao Wang - Probing New Physics at Future Lepton Colliders

**Wednesday:**

Haijun Yang - CEPC Detector Design and Physics Simulation

Gang Li - The Status of Detector Simulation and Physics Analysis of CEPC

Yaquan Fang - Preliminary Study on the Measurements of Higgs with CEPC

I will only be able to talk about a few selected topics, but yet there will be overlaps – my apology...
Historical Development

In 1964, three teams published in Phys. Rev. Lett. proposals on how mass could arise in local gauge theories. They are now credited for the BEH mechanism and Higgs boson.

L to R: Kibble, Guralnik, Hagen, Englert, and Brout

2013 Nobel Prize!
The Higgs boson mass is the only free parameter in the SM, everything else is predicted in the model...

SM @ 125 GeV: $\Gamma_H \approx 4.07$ MeV smaller than the experimental resolutions of direct measurements
The Discovery

July 4, 2012

Both ATLAS and CMS collaborations claimed excesses of $\sim 5\sigma$ significance.

No other scientific discovery has attracted such fanfare worldwide.

*The discovery was made based on the analysis of bosonic decays. There were no results of fermionic decays at the time of the discovery.*
Since the Discovery

LHC continued to take data since the discovery, more than double of the data size.

The additional data improve the significance of the signal and allow for more precise measurements of properties.

Both ATLAS and CMS have about 10σ significance!
Rates and Couplings

Always measure the rates \((\sigma \times BR) \Rightarrow \) only ratios can be determined in a model-independent way.

\[
(\sigma \cdot BR) (gg \to H \to ZZ^* \to 4\ell) = 
\left[\sigma(gg \to H) \cdot BR(H \to ZZ^* \to 4\ell)\right]_{SM} \times \frac{k_g^2 \cdot k_Z^2}{k_H^2}
\]

SM: \(\lambda \propto m\) (fermions)
\(g \propto m^2\) (bosons)

Rates and couplings are SM like!
Spin/CP Tests

Higgs decay kinematics depends on its properties of spin and parity. $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ final states have been analyzed to determine these properties.

SM prediction of $J^p=0^+$ is strongly favored, most alternatives studied are excluded @ 95% CL or higher.

$H \rightarrow \gamma\gamma$
Status at a Glance

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$H \rightarrow \gamma\gamma$</th>
<th>$H \rightarrow ZZ^*$</th>
<th>$H \rightarrow WW^*$</th>
<th>$H \rightarrow \tau\tau$</th>
<th>$H \rightarrow bb$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM BR (%)</td>
<td>0.23</td>
<td>2.63</td>
<td>21.5</td>
<td>6.32</td>
<td>57.7</td>
</tr>
<tr>
<td>ATLAS</td>
<td>5.2</td>
<td>6.6</td>
<td>5.8</td>
<td>4.1</td>
<td>1.4</td>
</tr>
<tr>
<td>CMS</td>
<td>5.7</td>
<td>6.8</td>
<td>4.3</td>
<td>3.4</td>
<td>2.1</td>
</tr>
<tr>
<td>SM BRs quoted for $m_H = 125$ GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Discovery-level significances in three bosonic decay modes; Weakest signal in $H \rightarrow bb$, the decay mode with the largest BR !

The question remains: Is the new boson solely responsible for the electroweak symmetry breaking?

Two parallel approaches:  
1. precise property measurements (subject of this presentation);  
2. direct searches of exotic decays as well as additional Higgs bosons.
US Snowmass Studies

A year-long study to examine the physics potential of future facilities

• The discovery of a ~125 GeV Higgs boson has opened a new era in the exploitation of electroweak symmetry breaking. There are many rich physics to be studied.

• LHC is the place to be to study the Higgs boson and search for additional Higgs bosons in the foreseeable future. It is a Higgs factory and can do precision measurements!

• Precision tests of Higgs boson properties to the level of one-percent will require complementary precision programs. Proposed Higgs factories will be able to achieve these precisions.

• Full exploitation of the Higgs measurements will require advances in theoretical calculations of production cross sections and decay branching ratios as well as precision in inputs to these calculations.
Hadron Colliders

Huge background
QCD production dominates $\sigma$
tiny S/B ratio: $\sigma_h/\sigma_{tot} \ll 10^{-11}$
unknown event level $\sqrt{s}$
messy collision environment

Trigger is the key!

On the other hand...
broad band in $\sqrt{s}$
much large Higgs cross section

At HL-LHC
170 millions of Higgs events
Production Cross Sections

Strong production dominates, difficult to calculate precisely,...
⇒ large uncertainties in the predictions

Theoretical:
  high order QCD corrections

Parametric:
  PDF and $\alpha_s$ uncertainties

Limit the interpretation of the measurements

<table>
<thead>
<tr>
<th>Process</th>
<th>QCD scale</th>
<th>PDF+$\alpha_s$</th>
<th>Total (linear sum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>±8%</td>
<td>±8%</td>
<td>±15%</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>±7%</td>
<td>±8%</td>
<td>±15%</td>
</tr>
<tr>
<td>VBF</td>
<td>±1%</td>
<td>±4%</td>
<td>±5%</td>
</tr>
<tr>
<td>VH</td>
<td>±1%</td>
<td>±4%</td>
<td>±5%</td>
</tr>
</tbody>
</table>
Cases for a Precision Higgs Program

How large are potential deviations from BSM physics? How well do we need to measure them to be sensitive?

To be sensitive to a deviation $\Delta$, the measurement precision needs to be much better than $\Delta$, at least $\Delta/3$ and preferably $\Delta/5$!

Since the couplings of the 125 GeV Higgs boson are found to be very close to SM $\Rightarrow$ deviations from BSM physics must be small.

Typical effect on coupling from heavy state $M$ or new physics at scale $M$:

$$\Delta \propto \left( \frac{\nu}{M} \right)^2 \ll 6\% @ M = 1\,\text{TeV}$$

(Han et al., hep-ph/0302188, Gupta et al. arXiv:1206.3560, ...)

MSSM decoupling limit

$\Delta$ at sub-percent to a few percent, will be challenging to distinguish the MSSM decoupling limit from the SM in the case of no direct discovery.

$\Rightarrow$ Need percent-level or better measurements!
Beyond the Standard Model

The Standard Model Higgs sector consists of one $\text{SU}(2)$ Higgs doublet field
\[ \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \]

Simple extensions to the SM Higgs sector:
- SM + a singlet $S$ (real or complex);
- SM + an additional Higgs doublet, known as 2 Higgs doublet model (2HDM);
- 2HDM + a singlet $S$;
- Higgs triplet model; ......

Why extensions?
- May provide a dark-matter candidate (Higgs portal model);
- May offer explanation for the electroweak phase transition; ......

Phenomenological and experimental consequences:
- Non-SM-like Higgs bosons $\Rightarrow$ coupling modifications;
- Additional neutral and/or charged Higgs bosons;
- New production processes and decay modes; ....
Electroweak production cross sections are predicted with (sub)percent level precisions in most cases.

Relative low rate can trigger on every event.

Well defined collision energy allow for the “missing” mass reconstruction (e.g., recoiling mass).

Clean events, smaller background small number of processes.

Ideal for precisions: measurements or searches.
Proposed $e^+e^-$ Colliders

ILC in Japan

Electrons

Positron source

Detectors

Electron source

Beam delivery systems

Main Linac

Damping Rings

Main Linac

There is also CLIC, see the presentation by Frank Simon
A Success Story: LEP

LEP-1 was first built as a Z factory (though it initially had top quark in sight), it was widely successful...

About 17 millions of Z bosons were produced, key physics
- Number of light neutrino species;
- Precision electroweak measurements;
- Direct search and indirect constraint on the Higgs boson; ...
Higgs Physics at $e^+e^-$ Colliders

A precision Higgs physics program is a key component of all proposals, difference is in energy and luminosity. Physics should have little difference for the same energy and luminosity.

**CEPC**  $\sqrt{s} \in 240 – 250$ GeV, focusing on measurements with $ee \rightarrow ZH$ with some contributions from $ee \rightarrow \nu\nu H$.

**FCC-ee (TLEP)**

same as CEPC, but $\sqrt{s}$ up to 350 GeV, significantly increase $ee \rightarrow \nu\nu H$ cross section.

**ILC**

higher $\sqrt{s}$, looked at 250 GeV and 500 GeV for Higgs physics

<table>
<thead>
<tr>
<th>Proposal</th>
<th>CEPC (2 IP)</th>
<th>TLEP (4 IP)</th>
<th>ILC*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>250</td>
<td>240 350</td>
<td>250 500</td>
</tr>
<tr>
<td>$\int L dt$ (ab$^{-1}$)</td>
<td>5</td>
<td>10 2.6</td>
<td>0.25 0.5</td>
</tr>
<tr>
<td># ZH events</td>
<td>1,000,000</td>
<td>2,000,000 340,000</td>
<td>75,000 50,000</td>
</tr>
<tr>
<td># $\nu\nu H$ events</td>
<td>30,000</td>
<td>50,000 70,000</td>
<td>3,000 75,000</td>
</tr>
</tbody>
</table>

* Baseline design with polarization.
## Accessible Decay Modes

Numbers of Higgs events: $\mathcal{O} 10^6$ at Higgs factories, $\mathcal{O} 10^8$ at HL-LHC

<table>
<thead>
<tr>
<th>SM decay mode</th>
<th>SM decay branching ratio</th>
<th>(HL-)LHC Accessible?</th>
<th>Higgs factories Accessible?</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to bb$</td>
<td>57.7%</td>
<td>✓, × *</td>
<td>✓</td>
</tr>
<tr>
<td>$H \to gg$</td>
<td>8.57%</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>$H \to cc$</td>
<td>2.91%</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>$H \to ss$</td>
<td>$2.46 \times 10^{-4}$</td>
<td>×</td>
<td>?</td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>6.32%</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$H \to \mu\mu$</td>
<td>$2.19 \times 10^{-4}$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$H \to WW$</td>
<td>21.5%</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$H \to ZZ$</td>
<td>2.64%</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>0.23%</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$H \to Z\gamma$</td>
<td>0.15%</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

* Not all production mode.

**Limitations:** statistics at Higgs factories, trigger and systematics at (HL-)LHC

Higgs factories are sensitive to unknown unknown decays while HL-LHC may be sensitive to known unknown decays (eg $H \to \text{inv}$).
Higgs Boson Production

At $\sqrt{s} \approx 240–250$ GeV, $ee \rightarrow ZH$ production is maximum and dominates with a smaller contribution from $ee \rightarrow \nu\nu H$.

Beyond that, the cross section decreases asymptotically as $1/s$ for $ee \rightarrow ZH$ and increases logarithmically for $ee \rightarrow \nu\nu H$.

![Graph showing Higgs boson production cross sections](image)

$\sqrt{s} = 250$ GeV: $\sigma_{ZH} \approx 200$ fb, $\sigma_{\nu\nu H} \approx 10$ fb
Higgs Tagging

Unique to lepton colliders, the energy and momentum of the Higgs boson in $ee \rightarrow ZH$ can be measured by looking at the Z kinematics only:

$$E_H = \sqrt{s} - E_Z, \quad \vec{p}_H = -\vec{p}_Z$$

Recoil mass reconstruction:

$$m^2_{\text{recoil}} = \left( \sqrt{s} - E_Z \right)^2 - |\vec{p}_Z|^2$$

$\Rightarrow$ identify Higgs without looking at Higgs.

Measure $\sigma (ee \rightarrow ZH)$ independent of its decay!
Recoiling Mass Distributions

Good recoil mass resolution for $Z \rightarrow \ell\ell$

A perfect validation sample in $ZZ \rightarrow \ell\ell + X$

$ZH$: detector resolution dominates the width, radiation dominates the tail

Utilized extensively for Higgs searches at LEP
Mass and Cross Section

The Higgs boson mass and the $ee \rightarrow ZH$ cross section can be extracted from the recoil mass spectra:

resonance peak $\approx M_H$, resonance height $\sigma(ee \rightarrow ZH)$

$\Delta M_H \approx 5.5$ MeV
from leptonic decays $Z \rightarrow ee, \mu\mu$
(resolution important)

$\Delta \sigma_{ZH}/\sigma_{ZH} \approx 0.5$
from $Z \rightarrow ee, \mu\mu$ and qq decays
(statistics important)
Branching Ratios

Examining the rest of the events to study Higgs boson decays and measure

$$\sigma(ee \rightarrow ZH) \times BR(H \rightarrow XX)$$

thus allowing the measurements of Higgs decay BR without assumptions.

$$H \rightarrow hadrons$$

Apply flavor tagging to separate $$H \rightarrow bb, cc, gg$$
Total Decay Width

The SM predicted value of $\Gamma_H \approx 4$ MeV is much smaller than the experimental resolution (\( \approx \) GeV) of the recoil mass $\Rightarrow$ cannot measured directly with a reasonable precision.

The Higgs total width can be inferred from the cross section and branching ratio measurements in a model-independent way. Two independent measurements:

$$\sigma(ee \to ZH): \quad \Gamma_H = \frac{\Gamma(H \to ZZ^*)}{BR(H \to ZZ^*)} \propto \frac{\sigma(ee \to ZH)}{BR(H \to ZZ^*)} \left( \text{Limited by the } H \to ZZ^* \text{ statistics} \right)$$

$$\sigma(ee \to \nu\nu H \to \nu\nu bb): \quad \Gamma_H = \frac{\Gamma(H \to bb)}{BR(H \to bb)} \propto \frac{\sigma(ee \to \nu\nu H \to \nu\nu bb)}{BR(H \to bb)\cdot BR(H \to WW^*)} \left( \text{Limited by the } ee \to \nu\nu H \to \nu\nu bb \text{ statistics} \right)$$
## ZH Rate Measurements

Most of these measurements are statistics limited, and the differences between different facilities are mostly due to statistics too.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\int L dt$</td>
<td>5 ab$^{-1}$</td>
<td>10 ab$^{-1}$</td>
<td>0.25 ab$^{-1}$</td>
<td>0.5 ab$^{-1}$</td>
</tr>
<tr>
<td>$\Delta M_H$</td>
<td>5.5 MeV</td>
<td>7 MeV</td>
<td>32 MeV</td>
<td>--</td>
</tr>
<tr>
<td>$\sigma_{ZH}$</td>
<td>0.5%</td>
<td>0.4%</td>
<td>2.6%</td>
<td>3.0%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \times \text{BR}(H \rightarrow bb)$</td>
<td>0.25%</td>
<td>0.2%</td>
<td>1.2%</td>
<td>1.8%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \times \text{BR}(H \rightarrow cc)$</td>
<td>3.2%</td>
<td>1.2%</td>
<td>8.3%</td>
<td>13%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \times \text{BR}(H \rightarrow gg)$</td>
<td>1.3%</td>
<td>1.4%</td>
<td>7.0%</td>
<td>11%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \times \text{BR}(H \rightarrow \tau\tau)$</td>
<td>1.2%</td>
<td>0.7%</td>
<td>4.2%</td>
<td>5.4%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \times \text{BR}(H \rightarrow \mu\mu)$</td>
<td>22%</td>
<td>13%</td>
<td>100%</td>
<td>--</td>
</tr>
<tr>
<td>$\sigma_{ZH} \times \text{BR}(H \rightarrow WW)$</td>
<td>1.5%</td>
<td>0.9%</td>
<td>6.4%</td>
<td>9.2%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \times \text{BR}(H \rightarrow ZZ)$</td>
<td>4.3%</td>
<td>3.1%</td>
<td>18%</td>
<td>25%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \times \text{BR}(H \rightarrow \gamma\gamma)$</td>
<td>8.2%</td>
<td>3.0%</td>
<td>34%</td>
<td>34%</td>
</tr>
</tbody>
</table>

95% CL upper limit

| BR$(H \rightarrow \text{inv})$ | 0.28% | 0.19% | 0.9% | 0.9% |

**Coupling Scale Parameters**

Parametrizing deviations from SM using scale parameters: $\kappa$ (SM: $\kappa = 1$)

\[
g_{Hff} = \frac{m_f}{v}, \quad g_{HVV} = \frac{2m_V}{v} \quad \Rightarrow \quad g_{Hff} = \kappa_f \cdot \frac{m_f}{v}, \quad g_{HVV} = \kappa_V \cdot \frac{2m_V}{v}
\]

For example: \( (\sigma \cdot BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \left[ \sigma(gg \rightarrow H) \cdot BR(H \rightarrow \gamma\gamma) \right]_{SM} \times \frac{\kappa_g^2 \cdot \kappa_{\gamma}^2}{\kappa_H^2} \)

$\kappa_H^2$ is the scale factor to the total Higgs decay width

\[
\kappa_H^2 = \sum_x \kappa_{x}^2 \cdot BR(H \rightarrow xx)
\]

- No non-SM decays \( \Rightarrow \kappa_H^2 = \sum_x \kappa_{x}^2 \cdot BR_{SM}(H \rightarrow xx) \)

- With non-SM decays \( \Rightarrow \kappa_H^2 = \sum_x \kappa_{x}^2 \cdot \frac{BR_{SM}(H \rightarrow xx)}{1 - BR_{non-SM}} \)

Benchmark models with different assumptions. Most models at LHC assume no non-SM decays \( (BR_{non-SM} = 0) \). More generally: \( BR_{non-SM} = BR_{inv} + BR_{exotic} \)
Coupling Fit Models

Most general model: one modifier per observable Higgs coupling

With $\geq 10^6$ events, the Higgs factories will be able to explore Higgs couplings to 9 fundamental particles in SM

- No direct access to $Htt$ coupling at $\sqrt{s} \sim 240 - 250$ GeV, sensitivity through the $H \rightarrow gg$ loop
- + sensitive BSM $H \rightarrow$ invisible decay
- + sensitive to other exotic decays with unknown signature through the total width

Model-independent coupling fit: 10 parameter

$$\kappa_b, \kappa_c, \kappa_t, \kappa_\mu, \kappa_Z, \kappa_W, \kappa_\gamma, \kappa_g, BR_{inv}, \Gamma_h$$
## Results of Coupling Fits

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\int L dt$</td>
<td>5 ab$^{-1}$</td>
<td>10 ab$^{-1}$</td>
<td>0.25 ab$^{-1}$</td>
<td>0.25+0.5 ab$^{-1}$</td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>2.7%</td>
<td>1.9%</td>
<td>12%</td>
<td>5.0%</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>1.3%</td>
<td>0.88%</td>
<td>5.3%</td>
<td>1.7%</td>
</tr>
<tr>
<td>$\kappa_c$</td>
<td>2.1%</td>
<td>1.0%</td>
<td>6.8%</td>
<td>2.8%</td>
</tr>
<tr>
<td>$\kappa_T$</td>
<td>1.4%</td>
<td>0.94%</td>
<td>5.7%</td>
<td>2.4%</td>
</tr>
<tr>
<td>$\kappa_\mu$</td>
<td>11%</td>
<td>6.4%</td>
<td>91%</td>
<td>91%</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>1.2%</td>
<td>0.85%</td>
<td>4.8%</td>
<td>1.2%</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>0.25%</td>
<td>0.16%</td>
<td>1.3%</td>
<td>1.0%</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>1.5%</td>
<td>1.1%</td>
<td>6.4%</td>
<td>2.3%</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>4.3%</td>
<td>1.7%</td>
<td>18%</td>
<td>8.4%</td>
</tr>
</tbody>
</table>

95% CL upper limit

| BR($H \rightarrow \text{inv}$) | 0.28% | 0.19% | 0.9% | 0.9% |


Note: ILC 500+ will be able to measure $\kappa_t$ directly as well.

Percent-level or better precision for many couplings
Comparisons with LHC

Fully model-independent fit is not possible at the LHC

7-parameter model:

$$K_c, K_b, K_\ell, K_W, K_Z, K_g, K_\gamma$$

Assumptions:

- no BSM decays
- up-type quarks: $$K_u = K_c = K_t$$
- down-type quarks: $$K_d = K_s = K_b$$
- charged leptons: $$K_e = K_\mu = K_\tau$$

CEPC vs HL-LHC

Order of magnitude improvements

Expected over the HL-LHC

HL-LHC: ATL-PHYS-PUB-2014-016
Spin/CP Tests

ZH threshold scan

\[ \sigma \propto f(\beta) \]: different \( \beta \) dependence in the threshold region

Far above the threshold, \( ZH \) dominated by longitudinal \( Z \) production \( \Rightarrow \sigma(\theta) \propto \sin^2 \theta \) for scalar pair production

ILC arXiv:1310.0763
Higgs Self-coupling

\[ \sqrt{s} \geq 500 \text{ GeV} \]

\[ (\text{ILC} + \text{CLIC}) \]

\[ V(\phi) = \mu^2 (\phi^\dagger \phi) + \lambda (\phi^\dagger \phi)^2 \]

Low rates:

\~400 events total at ILC
\~1000 events at CLIC

and there is a significant contamination from continuum HH production

\[ \Rightarrow \frac{\Delta \lambda}{\lambda} \sim 26\% \text{ (ILC), 16\% (CLIC)} \]
**μ⁺μ⁻ Collider – Lineshape Scan**

\[
\sigma(\mu^+\mu^- \rightarrow h \rightarrow X) = \frac{4\pi\Gamma_h^2 \text{Br}(h \rightarrow \mu^+\mu^-)\text{Br}(h \rightarrow X)}{(s - m_h^2)^2 + \Gamma_h^2 m_h^2}.
\]

Han & Liu: arXiv:1210.7803

Similar to Z scan at LEP!

**Studied two cases:**

\[
R = 0.01\% (\Delta = 8.9 \text{ MeV}), \quad L = 0.5 \text{ fb}^{-1}
\]

\[
R = 0.003\% (\Delta = 2.7 \text{ MeV}), \quad L = 1 \text{ fb}^{-1}
\]

Expect to measure both mass and total width with sub-MeV precision
Selective production of Spin and CP states through photon polarization

- circular polarization $\Rightarrow$ J=0,2
- linearly polarization $\Rightarrow$ CP states

- $\gamma \perp \gamma \Rightarrow$ CP even
- $\gamma \parallel \gamma \Rightarrow$ CP odd

Large $\sigma(\gamma\gamma \rightarrow H) \sim 1$ pb

Expect $\sim 2\%$ precision on $\Gamma_{\gamma\gamma}$

Ideal for studying Spin/CP properties of the Higgs boson

Boos et al., NIM A472, 100 (2001)
Summary

By all measures, the properties of the 125 GeV particle are consistent with the expectations of the SM Higgs boson. LHC will continue to explore the electroweak symmetry breaking and improve the precisions of its Higgs measurements.

Theoretically, BSM Higgs phenomena predict deviations from SM, but at levels likely below the LHC precisions.

A lepton collider Higgs factory complements to LHC. It allows for mode-independent measurements of the Higgs boson properties and can significantly improve their precisions.

Such a facility has the potential to “undress” the Higgs boson as what LEP has done to the Z boson, and possibly shed light on the direction of new physics.
Expected Coupling Deviations

Typical effect on coupling from heavy state (or new physics scale) $M$:

\[ \Delta \left( \frac{\nu}{M} \right)^2 \lesssim 6\% \text{ at } M \gtrsim 1 \text{ TeV} \]

(Han et al., hep-ph/0302188, Gupta et al. arXiv:1206.3560, ...)

Typical sizes of coupling modification from some selected BSM models

<table>
<thead>
<tr>
<th>Model</th>
<th>$\kappa_V$</th>
<th>$\kappa_b$</th>
<th>$\kappa_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet Mixing</td>
<td>$\sim 6%$</td>
<td>$\sim 6%$</td>
<td>$\sim 6%$</td>
</tr>
<tr>
<td>2HDM</td>
<td>$\sim 1%$</td>
<td>$\sim 10%$</td>
<td>$\sim 1%$</td>
</tr>
<tr>
<td>Decoupling MSSM</td>
<td>$\sim -0.0013%$</td>
<td>$\sim 1.6%$</td>
<td>$&lt;1.5%$</td>
</tr>
<tr>
<td>Composite</td>
<td>$\sim -3%$</td>
<td>$\sim -(3-9)%$</td>
<td>$\sim -9%$</td>
</tr>
<tr>
<td>Top Partner</td>
<td>$\sim -2%$</td>
<td>$\sim -2%$</td>
<td>$\sim +1%$</td>
</tr>
</tbody>
</table>

Snowmass Higgs report, arXiv:1310.8361

The precisions of the current coupling fits are insensitive to new physics at TeV scale...
The Search

World-wide hunt for the past several decades, major physics objectives of LEP, Tevatron and the LHC with increasing

(My career: L3 → Dzero → ATLAS)
**Coupling Comparison (Snowmass)**

ILC projections are from Tim Barklow. The rest is mostly taken from the presentation by Patrick Janot at the BNL workshop. The LHC numbers are *per experiment* (unless noted) of CMS projections of two scenarios of systematics assumptions.

<table>
<thead>
<tr>
<th>Facility</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC</th>
<th>Full ILC</th>
<th>CLIC</th>
<th>LEP3 (4 IP)</th>
<th>TLEP (4 IP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>14,000</td>
<td>14,000</td>
<td>250</td>
<td>250+500+1000</td>
<td>350+500+1500</td>
<td>240</td>
<td>240+350</td>
</tr>
<tr>
<td>$\int L dt$ (fb$^{-1}$)</td>
<td>300/expt</td>
<td>3000/expt</td>
<td>250</td>
<td>250+500+1000</td>
<td>500+500+1500</td>
<td>2000</td>
<td>10000+1400</td>
</tr>
<tr>
<td>$N_H$ produced</td>
<td>$1.7 \times 10^7$</td>
<td>$1.7 \times 10^8$</td>
<td>80,000</td>
<td>370,000</td>
<td>618,000</td>
<td>600,000</td>
<td>3,200,000</td>
</tr>
</tbody>
</table>

| $m_H$ (MeV) | 100 | 50 | 35 | 35 | 70 | 26 | 7 |
| $\Delta \Gamma_H$ | – | – | 11% | 6% | 6% | 4% | 1.3% |
| BR$^{\text{inv}}$ | NA | NA | <0.8% | <0.8% | NA | <0.7% | <0.3% |
| $\Delta g_{H\gamma\gamma}$ | 5.1 – 6.5% | 1.5 – 5.4% | 18% | 4.1% | NA | 3.4% | 1.4% |
| $\Delta g_{Hgg}$ | 5.7 – 11% | 2.7 – 7.5% | 6.4% | 1.8% | NA | 2.2% | 0.7% |
| $\Delta g_{HHWW}$ | 2.7 – 5.7%$^\dagger$ | 1.0 – 4.5%$^\dagger$ | 4.8% | 1.4% | 1% | 1.5% | 0.25% |
| $\Delta g_{HHZZ}$ | 2.7 – 5.7%$^\dagger$ | 1.0 – 4.5%$^\dagger$ | 1.3% | 1.3% | 1% | 0.25% | 0.2% |
| $\Delta g_{HH\mu\mu}$ | < 30% | < 10% | – | 16% | 15% | 14% | 7% |
| $\Delta g_{HH\tau\tau}$ | 5.1 – 8.5% | 2.0 – 5.4% | 5.7% | 2.0% | 3% | 1.5% | 0.4% |
| $\Delta g_{HHcc}$ | – | – | 6.8% | 2.0% | 4% | 2.0% | 0.25% |
| $\Delta g_{HHbb}$ | 6.9 – 15% | 2.7 – 11% | 5.3% | 1.5% | 2% | 0.7% | 0.22% |
| $\Delta g_{HHtt}$ | 8.7 – 14% | 3.9 – 8.0% | – | 4.0% | 3% | – | 30% |
| $\Delta g_{HHHH}$ | – | 30%$^\ddagger$ | – | 26% | 16% | – | – |

Note: with the luminosity upgrade, the ILC coupling precision improves by a factor of ~ 2.

$^\dagger$ assuming the same deviation for the HWW and HZZ couplings. $^\ddagger$ two experiments.
In SM, the $gg \rightarrow H$ cross section can be broken into three pieces: $\sigma_{SM} = \sigma_{tt} + \sigma_{bb} + \sigma_{tb}$

With coupling modifications, the cross section becomes $\Rightarrow \sigma = K_t^2 \sigma_{tt} + K_b^2 \sigma_{bb} + K_t K_b \sigma_{tb}$

The effective $Hgg$ coupling scale parameter is

$K_g^2 = \frac{\sigma}{\sigma_{SM}} = \frac{K_t^2 \sigma_{tt} + K_b^2 \sigma_{bb} + K_t K_b \sigma_{tb}}{\sigma_{tt} + \sigma_{bb} + \sigma_{tb}}$

$\approx 1.058 K_t^2 + 0.007 K_b^2 - 0.065 K_t K_b^*$

$K_{\gamma}^2 = \frac{\Gamma_{\gamma\gamma}}{\Gamma_{SM}^{\gamma\gamma}} = \frac{K_t^2 \Gamma_{tt}^{\gamma\gamma} + K_b^2 \Gamma_{WW}^{\gamma\gamma} + K_t K_b \Gamma_{tW}^{\gamma\gamma}}{\Gamma_{tt}^{\gamma\gamma} + \Gamma_{WW}^{\gamma\gamma} + \Gamma_{tW}^{\gamma\gamma}}$

$\approx 0.07 K_t^2 + 1.59 K_b^2 - 0.66 K_t K_b^*$

$^*$ $m_H = 125.5$ GeV