Future Prospects for Brout-Englert-Higgs (-Guralnik-Hagen-Kibble) Bosons

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ICNFP14
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*‘Higgs’ =BEHGHK
(Brout-Englert-Higgs-Guralnik-Hagen-Kibble)
Introduction

Upgraded LHC Upgrades calendar and experimental challenge

Assumptions, methods and scenarios

Properties of the observed Higgs boson: Signal strengths, couplings/coupling ratios, natural Width, Invisible Branching Fraction and Higgs-Portal Interpretation, Field Strength Tensor Structure, rare Decays: $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$, $t \rightarrow cH$, $H \rightarrow \gamma\gamma$ (FCNC), $VH \rightarrow \ell^+ + b\bar{b}$, $VH/\ell^+ + \ell^- + b\bar{b}$ and $H \rightarrow g\gamma$

Search for additional (BSM) Higgs bosons: Indirect from coupling measurements, direct from $H/A \rightarrow \mu\mu$

$H \rightarrow ZZ \rightarrow 4\ell$

$A \rightarrow Z\gamma \rightarrow \ell^+ \ell^- b\bar{b}$

Future Colliders Introduction to the machines and physics

Coupling measurements

BSM prospects

Summary and Conclusion

Acknowledgements

This result constitutes evidence for the existence of a new massive state that decays into two photons.

Clear evidence for the production of a neutral boson ... is presented.

In Runs 2-3-4-5... and beyond...
- Continue to measure its properties
- Is it alone?

Production and Decay at the Run2 LHC

Production

{Production diagrams with particles and processes}

Decay

{Decay diagrams with particles and processes}

Phase 1 Upgrade ➔ Run 3 (2020-2022): twice LHC design luminosity
Event pileup reaches ~50-60 collisions per beam crossing (@ 25 ns)
Factor 5 increase in trigger rates relative to 2012 run

Phase 2 Upgrade ➔ HL-LHC Runs 4,5,.. (2025-2035+…): 5-7x LHC design luminosity
Event pileup reaches ~140 collisions per beam crossing (@ 25 ns)
Need solutions to cope with very high rates (10-15 x 2012), radiation and pileup

with design $L = 1-2 \times 10^{34} \, \text{cm}^{-2} \text{s}^{-1}$
LHC: The ATLAS Experiment
LHC: The CMS Experiment

Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m

ECAL
76k scintillating PbWO$_4$ crystals

HCAL
Scintillator/brass Interleaved ~7k ch

3.8T Solenoid

Pixel Tracker

ECAL

HCal

Muons Solenoid coil

 Pixels & Tracker
- Pixels (100x150 µm$^2$)
  ~ 1 m$^2$ ~66M ch
- Si Strips (80-180 µm)
  ~200 m$^2$ ~9.6M ch

MUON BARREL
250 Drift Tubes (DT) and 480 Resistive Plate Chambers (RPC)

MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)

Preshower
Si Strips ~16 m$^2$
~137k ch

Foward Cal
Steel + quartz Fibers 2~k ch

IRON YOKE

## Phase II detector upgrades

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>4 barrel layers, 6 discs/endcap</td>
<td>4 barrel layers, 5 discs/endcap extend to $</td>
</tr>
<tr>
<td></td>
<td>100...150μm thickness</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25 x 150μm² size</td>
<td></td>
</tr>
<tr>
<td>Inner tracker</td>
<td>Full silicon, low material $\leq 0.5X_0$ for $</td>
<td>η</td>
</tr>
<tr>
<td>ECAL barrel</td>
<td>replace frontend electronics</td>
<td></td>
</tr>
<tr>
<td>ECAL endcap</td>
<td>-</td>
<td>Shashlik (W or Pb absorber + scintillator)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silicon High Granularity Calorimeter</td>
</tr>
<tr>
<td>HCAL barrel</td>
<td>replace frontend electronics</td>
<td>-</td>
</tr>
<tr>
<td>HCAL endcap/forward</td>
<td>-</td>
<td>Use radiation hard scintillator, potentially increase transverse segmentation / HGC</td>
</tr>
</tbody>
</table>
Assumptions, methods and scenarios

**ATLAS**: Use fast simulation to mimic the beam effects on momentum and energy resolution, acceptance, identification and reconstruction efficiencies, fake rates, etc. Some rescaling of Run1 results for some analyses.

**CMS**: Assume that upgraded detector will compensate the effects of higher pile-up, use three different scenarios:

1. **Scenario 1**: all systematic uncertainties are kept unchanged with respect to those in current data analyses
2. **Scenario 2**: the theoretical uncertainties are scaled by a factor of $1/2$, while other systematical uncertainties are scaled by $1/\sqrt{L}$
3. **Scenario 3**: set theoretical uncertainties to zero, leave other systematical uncertainties the same as in 2012

Some studies with fast simulation

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*S. Gascon-Shotkin ‘Future Prospects for BEHHGK Bosons’, OAC Kolymbari, Crete. July 30 2014*
**Higgs Boson Properties: Signal Strengths \( \mu = \sigma/\sigma_{SM} \)**

### ATLAS Simulation Preliminary

<table>
<thead>
<tr>
<th>Process</th>
<th>( \mu )</th>
<th>( \Delta \mu/\mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \to \mu\mu )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(comb.)</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>(incl.)</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>(tH-like)</td>
<td></td>
<td></td>
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<tr>
<td>(VH-like)</td>
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<tr>
<td>(tH-like)</td>
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<td></td>
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<tr>
<td>(VBF-like)</td>
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<td></td>
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<tr>
<td>(ggF-like)</td>
<td></td>
<td></td>
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<tr>
<td>( H \to \tau\tau )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(VBF-like)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(+1j)</td>
<td></td>
<td></td>
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<tr>
<td>(+0j)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H \to W W )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(VBF-like)</td>
<td></td>
<td></td>
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<tr>
<td>(+1j)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(+0j)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H \to Z \gamma )</td>
<td></td>
<td></td>
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<tr>
<td>(incl.)</td>
<td></td>
<td></td>
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<tr>
<td>( H \to \gamma\gamma )</td>
<td></td>
<td></td>
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<tr>
<td>(comb.)</td>
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<td>(+1j)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(+0j)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CMS Projection**

Expected uncertainties on Higgs boson signal strength:

- \( H \to \gamma\gamma \)
- \( H \to W W \)
- \( H \to Z Z \)
- \( H \to b b \)
- \( H \to \tau\tau \)

For \( H \to \gamma\gamma, WW, ZZ, bb, \tau\tau \):

- 300 fb\(^{-1}\): Ranges from 6-22\% (ATLAS), 6-14\% (CMS)
- 3000 fb\(^{-1}\): Ranges from 4-19\% (ATLAS), 4-8\% (CMS)

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**ATL-PHYS-PUB-2013-014**

Higgs Boson Properties: Couplings and Coupling ratios (1)

Global fit procedure of LHC-Higgs XS WG (arXiv:1307.1347), modifier for each $\kappa$, effective $\kappa$ for loops, $\kappa_H = \Sigma \kappa_i BR_i$ for i in SM

$$\sigma \cdot BR(ii \rightarrow H \rightarrow ff) = \sigma_{SM} \cdot BR_{SM} \frac{\kappa_i^2 \cdot \kappa}{\kappa_H^2}$$

### CMS Projection

- Expected uncertainties on Higgs boson couplings

<table>
<thead>
<tr>
<th>$\kappa$</th>
<th>Expected uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_\gamma$</td>
<td>0.00 0.05 0.10 0.15</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>0.00 0.05 0.10 0.15</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>0.00 0.05 0.10 0.15</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>0.00 0.05 0.10 0.15</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>0.00 0.05 0.10 0.15</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>0.00 0.05 0.10 0.15</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>0.00 0.05 0.10 0.15</td>
</tr>
</tbody>
</table>

### CMS Projection

<table>
<thead>
<tr>
<th>Expected uncertainties on Higgs boson couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_\gamma$</td>
</tr>
<tr>
<td>$\kappa_W$</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
</tr>
<tr>
<td>$\kappa_g$</td>
</tr>
<tr>
<td>$\kappa_b$</td>
</tr>
<tr>
<td>$\kappa_t$</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>$-2\Delta LnL = 1$, (%)</th>
<th>$\kappa_\gamma$</th>
<th>$\kappa_W$</th>
<th>$\kappa_Z$</th>
<th>$\kappa_g$</th>
<th>$\kappa_b$</th>
<th>$\kappa_t$</th>
<th>$\kappa_\tau$</th>
<th>$\kappa_{Z\gamma}$</th>
<th>$\kappa_\mu$</th>
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<tbody>
<tr>
<td>300 fb$^{-1}$ ATLAS</td>
<td>[8,13]</td>
<td>[6,8]</td>
<td>[7,8]</td>
<td>[8,11]</td>
<td>N/a</td>
<td>[20,22]</td>
<td>[13,18]</td>
<td>[78,79]</td>
<td>[21,23]</td>
</tr>
<tr>
<td>CMS</td>
<td>[5,7]</td>
<td>[4,6]</td>
<td>[4,6]</td>
<td>[6,8]</td>
<td>[10,13]</td>
<td>[14,15]</td>
<td>[6,8]</td>
<td>[41,41]</td>
<td>[23,23]</td>
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<tr>
<td>3000 fb$^{-1}$ ATLAS</td>
<td>[5,9]</td>
<td>[4,6]</td>
<td>[4,6]</td>
<td>[5,7]</td>
<td>N/a</td>
<td>[8,10]</td>
<td>[10,15]</td>
<td>[29,30]</td>
<td>[8,11]</td>
</tr>
<tr>
<td>CMS</td>
<td>[2,5]</td>
<td>[2,5]</td>
<td>[2,4]</td>
<td>[3,5]</td>
<td>[4,7]</td>
<td>[7,10]</td>
<td>[2,5]</td>
<td>[10,12]</td>
<td>[8,8]</td>
</tr>
</tbody>
</table>
Higgs Boson Properties: Couplings and Coupling ratios (2)

Fit coupling ratios to avoid assumption on total width
300fb⁻¹: Ranges from 3-22% (ATLAS), 4-23% (CMS)
3000fb⁻¹: Ranges from 2-10%(ATLAS), 2-8% (CMS)

<table>
<thead>
<tr>
<th></th>
<th>$$\kappa_g$$</th>
<th>$$\kappa_z$$</th>
<th>$$\kappa_w$$</th>
<th>$$\kappa_Z$$</th>
<th>$$\kappa_Y$$</th>
<th>$$\kappa_g$$</th>
<th>$$\kappa_z$$</th>
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<tr>
<td>300fb⁻¹</td>
<td>[3.6]</td>
<td>[4.5]</td>
<td>[5.11]</td>
<td>[11.12]</td>
<td>N/a</td>
<td>[11.13]</td>
<td>[20.22]</td>
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<tr>
<td></td>
<td>ATLAS</td>
<td>[4.6]</td>
<td>[4.7]</td>
<td>[5.8]</td>
<td>[6.9]</td>
<td>[8.11]</td>
<td>[6.9]</td>
</tr>
<tr>
<td></td>
<td>CMS</td>
<td>[2.5]</td>
<td>[2.3]</td>
<td>[2.7]</td>
<td>[5.6]</td>
<td>N/a</td>
<td>[7.10]</td>
</tr>
<tr>
<td>3000fb⁻¹</td>
<td>[2.5]</td>
<td>[2.3]</td>
<td>[3.5]</td>
<td>[3.5]</td>
<td>[2.4]</td>
<td>[3.5]</td>
<td>[2.4]</td>
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<tr>
<td></td>
<td>ATLAS</td>
<td>[2.5]</td>
<td>[2.3]</td>
<td>[2.5]</td>
<td>[3.5]</td>
<td>[3.5]</td>
<td>[2.4]</td>
</tr>
<tr>
<td></td>
<td>CMS</td>
<td>[2.5]</td>
<td>[2.3]</td>
<td>[3.5]</td>
<td>[3.5]</td>
<td>[2.4]</td>
<td>[3.5]</td>
</tr>
</tbody>
</table>

Precision on universal couplings to fermions (kF) and bosons (kV) at 1/2 sigma

~5% (10%) precision in Higgs couplings to vector bosons (fermions) with 3000fb-1

Mass-scaled coupling ratios

Higgs Boson Properties: Couplings and Coupling Ratios (3)

ATL-PHYS-PUB-2013-014

http://cds.cern.ch/record/1494600?ln=en

Higgs Boson Properties: Natural Width via $H \rightarrow \gamma\gamma$

1. $gg \rightarrow \gamma\gamma / gg \rightarrow H \rightarrow gg$ interference convoluted with detector resolution shifts mass peak, function of natural width ($\Gamma_{SM} = 4.1$ MeV), probeable via $p_{T_{\gamma\gamma}}$

2. 95% CL $\Gamma_H < 920$ (200) MeV for 300(3000)fb$^{-1}$


LB on $\Gamma / \Gamma_{SM}$

$\Delta M_{SM} = -54.4$ MeV

Higgs Boson Properties: Invisible Branching Fraction and Higgs-Portal Interpretation

Maximum LH fit to $E_{\text{miss}}$

<table>
<thead>
<tr>
<th>Higgs Boson Properties</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$300 \text{ fb}^{-1}$</td>
<td>[23,32]%</td>
<td>[17,28]%</td>
</tr>
<tr>
<td>$3000 \text{ fb}^{-1}$</td>
<td>[8,16]%</td>
<td>[6,17]%</td>
</tr>
</tbody>
</table>

Ind. couplings

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$300 \text{ fb}^{-1}$</td>
<td>[25,28]%</td>
<td>[14,18]%</td>
</tr>
<tr>
<td>$3000 \text{ fb}^{-1}$</td>
<td>[12,15]%</td>
<td>[7,11]%</td>
</tr>
</tbody>
</table>

95% UL on $\text{Br}_{\text{inv}}$ [real., cons.]:

Exclusion in $\sigma_{\text{DM-nucleon}} - m_{\text{DM}}$ plane: sensitivity up to $m_H/2$, complementary to direct detection DM experiments

95% CL

90% CL

Higgs Boson Properties: Field Strength Tensor Structure via $H \rightarrow ZZ^* \rightarrow 4l$

$$A(H \rightarrow ZZ) = v^{-1} \left( a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f^{(1)}_{\mu \nu} f^{(2), \mu \nu} + a_3 f^{(1)}_{\mu \nu} f^{(2), \mu \nu} \right)$$

- Test for presence of extra anomalous CP-even (coupling $a_2 \leftrightarrow g_2$) and CP-odd (coupling $a_3 \leftrightarrow g_4$) components
- 8D fit involving kinematical variables sensitive to $a_2$ and $a_3$ with free parameters $\text{Re}(a_i)/a_1$ and $\text{Im}(a_i)/a_1$, $i=\{2,3\}$

95% CL limits: (0,0) corresponds to pure CP-even ‘0+’ SM state

Factor $\sim 2-3$ improvement in precision between 300 and 3000fb-1
Higgs Boson Properties: Field Strength Tensor Structure via $H \rightarrow ZZ^* \rightarrow 4l$

$A(H \rightarrow ZZ) = \nu^{-1} \left( a_1 m_Z^2 e_1^* e_2^* + a_2 f_{\mu\nu}^{(1)} f^{(2),\mu\nu} + a_3 f_{\mu\nu}^{(1)} f^{(2),\mu\nu} \right)$

**SM tree process** loop CP-even contributions CP-odd contributions (BSM)

**Alternative method:** Fit fraction of events $f_{ai}$ and phases $\phi_i$ in 0-contribution to kinematic discriminant distribution

**95% CL limits:**

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>$f_{g_4}$</th>
<th>$f_{g_4}$</th>
<th>$f_{g_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 fb$^{-1}$</td>
<td>0.13</td>
<td>0.20</td>
<td>0.29</td>
</tr>
<tr>
<td>3000 fb$^{-1}$</td>
<td>0.04</td>
<td>0.06</td>
<td>0.12</td>
</tr>
</tbody>
</table>

CMS 95% CL ATLAS

ATLAS Simulation Preliminary

3000 fb$^{-1}$: 68%-95% CL
300 fb$^{-1}$: 68%-95% CL

8D Fit

CMS Projection

68% CL: 0.07 with 300 fb$^{-1}$
0.02 with 3000 fb$^{-1}$

ATLAS Simulation Preliminary

3000 fb$^{-1}$: 68%-95% CL
300 fb$^{-1}$: 68%-95% CL

8D Fit

Rare Decays: $H \to \mu\mu$ (probe 2\textsuperscript{nd} generation)

- Background from binned LH fit to the $\mu^+\mu^-$ mass distribution
- $tt\bar{t}H$, $H \to \mu\mu$ observability
- CMS: SM sensitivity after $\sim 150\text{fb}^{-1}$, 5$\sigma$ significance after $\sim 1200\text{fb}^{-1}$, $\sim 10\%$ precision possible on Yukawa coupling measurement

<table>
<thead>
<tr>
<th>$L$ [fb$^{-1}$]</th>
<th>300</th>
<th>3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal significance</td>
<td>$2.3\sigma$</td>
<td>$7.0\sigma$</td>
</tr>
<tr>
<td>$\Delta\mu/\mu$</td>
<td>46$%$</td>
<td>21$%$</td>
</tr>
</tbody>
</table>

**CMS Preliminary**

**Expected Significance**

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13007TWiki
Rare Decays: $H \rightarrow Z\gamma$

- Probe for new physics in charged particle loops
- Fit to $m_\gamma\gamma$ distribution in 3 categories in $pT\tau$ and $|\Delta\eta(Z,\gamma)|$

After 3000 fb$^{-1}$, sensitivity wrt SM expectation: 0.52, $p$-value for $m_H=125$ GeV: 3.9$\sigma$

Expected measured signal strength:

$$1.00^{+0.25}_{-0.26} (\text{stat.}) + 0.17 (\text{sys.})$$
Rare Decays: $t \to cH$, $H \to \gamma\gamma$ (FCNC)

- Include hadronic + leptonic $W$ decays, extrapolated acceptances 8-14 TeV
- SM: $\text{BR}(t \to cH) = 3 \times 10^{-15}$
- BSM: $\text{BR}(t \to cH)$ possibly as large as $\sim 10^{-5} - 10^{-3}$

95% CL limit on $\text{BR}(t \to cH)$ for tight jet $p_T$ cuts: $1.5-1.7 \times 10^{-4}$, $\to tcH$ coupling $< 0.024$ for 3000 fb$^{-1}$

Rare Decays in Lepton-Associated Production

**Based on Run1 analysis + improved b-tagging and multivariate signal selection**

- p-value for $m_H=125$ GeV after 300 (3000) fb-1: $2.6 \ (5.9)\sigma$
- Expected measured $H \rightarrow \text{bbar}$ signal strength precision: $\Delta \mu = 0.39 - 0.38 \ ( +/- 0.19)$

**Expected measured $H \rightarrow \gamma \gamma$ signal strength precision after 3000 fb-1 ranges between: $\Delta \mu = \{17\%, 35\%\}$ depending on channel**

\[
\begin{array}{|c|c|c|c|c|}
\hline
& \bar{t}H & WH & ZH & VBF \\
\hline
\text{Significance} & 8.2 & 4.2 & 3.7 & 3.8 \\
\hline
\end{array}
\]
Search for additional (BSM) Higgs bosons: from coupling measurement reinterpretation

Rescale production and decay rates as functions of the couplings $\kappa_V$, $\kappa_u$, $\kappa_d$, and $\kappa_\ell$
Search for additional (BSM) Higgs bosons via $H/A \rightarrow \mu\mu$

- Binned LH fit to the $\mu^+ \mu^-$ mass distribution, 2 categories (with and without b-tag)
- $5\sigma$ contours in the $\tan\beta$-$m_A$ plane in MSSM, mhMax scenario:

**ATLAS Preliminary, Simulation, $\sqrt{s} = 14$ TeV**

- Events/Bin
- $\int L dt = 3000$ fb$^{-1}$
- $\sqrt{s} = 14$ TeV

**ATLAS Preliminary, Simulation**

- Events/Bin
- $\int L dt = 3000$ fb$^{-1}$
- $\sqrt{s} = 14$ TeV

Search for additional (BSM) Higgs bosons via $H \rightarrow ZZ \rightarrow 4l$

$\sigma \times \text{BR}$ limits as function of $m_H$ 3000fb$^{-1}$ (ATLAS includes BR to 4l), probe up to factor 40 below SM.

**ATLAS Preliminary, Simulation**

$\int L \, dt = 3000 \, \text{fb}^{-1}$, $\sqrt{s} = 14$ TeV

- Expected CLs
- $1 \sigma$
- $2 \sigma$

$\sigma \times \text{BR}(H \rightarrow ZZ \rightarrow 4l)$

- gluon-fusion
- VBF production

**CMS Simulation 2013**

$\sqrt{s} = 14$ TeV $L = 3000 \, \text{fb}^{-1}$

- $H \rightarrow ZZ (m_H = 300 \, \text{GeV})$
- $H \rightarrow ZZ (m_H = 500 \, \text{GeV})$
- $H \rightarrow ZZ (m_H = 800 \, \text{GeV})$

**CMS-FTR-13-024**

Search for additional (BSM) Higgs bosons via $H \rightarrow ZZ \rightarrow 4\ell$

CMS: 5$\sigma$ contours in the $\tan\beta$-$\cos(\beta-\alpha)$ plane, 2HDM Types I, II for 3000fb$^{-1}$

Search for additional (BSM) Higgs bosons via $A \rightarrow Zh \rightarrow llbb$

- $\sigma \times BR$ limits as function of $m_A$, 3000fb$^{-1}$ (ATLAS includes BR to $llbb$)

Binned LH fit to $m_A$

Bin-by-bin counting experiment

$\int L dt = 3000 \text{ fb}^{-1}$, $\sqrt{s} = 14 \text{ TeV}$

$A \rightarrow Zh, m_A = 700 \text{ GeV}$

$\sigma_{gg \rightarrow A} \times BR(A \rightarrow Zh \rightarrow llbb)$ [fb]

$\sigma_{pp \rightarrow A} \times BR(A \rightarrow Zh)$ [fb]

$S. \text{ Gascon-Shotkin ‘Future Prospects for BEHHGK Bosons’, OAC Kolymbari, Crete, July 30 2014}$
Search for additional (BSM) Higgs bosons via $A \rightarrow Zh \rightarrow llbb$

Interpretation in 2HDM I, II

ATLAS Preliminary, Simulation

CMS Simulation 2013 $\sqrt{s} = 14$ TeV $L = 3000$ fb$^{-1}$

Type I

$A \rightarrow Zh$

$m_A = 500$ GeV

95% CL exclusion

5σ discovery potential

CMS-FTR-13-024

ATLAS Preliminary, Simulation

CMS Simulation 2013 $\sqrt{s} = 14$ TeV $L = 3000$ fb$^{-1}$

Type II

$A \rightarrow Zh$

$m_A = 500$ GeV

95% CL exclusion

5σ discovery potential

CMS-FTR-13-024

Prospects for measurements of properties of the observed Higgs boson:

- Signal strength precision: \(~20\%\) after 300 fb-1
  \(<15\%\) after 3000 fb-1
- Couplings and coupling ratios: \(~20\%\) after 300 fb-1
  \(<10\%\) after 3000 fb-1
- Natural Width: \(\Gamma_H < 920\) (200) MeV for 300(3000) fb-1 from \(H\rightarrow\gamma\gamma\), indep. technique from \(H\rightarrow4\ell\), less precise but theoretically more conservative
- Invisible branching fraction: similar for indirect and direct techniques,
  \(<\sim 30\%\) after 300 fb-1
  \(~15\%\) after 3000 fb-1
- Field strength tensor structure: fraction of CP-odd contribution
  \(<\sim 20\%\) after 300 fb-1, \(<10\%\) after 3000 fb-1
- Observation of rare decays: \(H\rightarrow\mu\mu\) possible in Run 3, the rest Run 4-5
- HH pair production and self-coupling: detection from \(tth-hhh\) interference,
  studies in progress, \(bb\tau^+\tau^-\), \(bb\gamma\gamma\) most promising, also \(bbZZ\) with one \(Z\rightarrow\ell\ell\) with \(\ell=\{e,\,\mu\}\) and the other \(Z\rightarrow\nu\nu\) worth further exploring

Prospects for searches for additional (BSM) Higgs bosons:

- Indirect from coupling measurements and direct: In both cases could probe large portions of 2HDM phase space starting even in Run 3

If challenges from pileup and trigger rates can be met, the upgraded LHC will provide the opportunity for precise measurements, and hopefully some surprises as well

Future e+e- H Physics program/ILC timetable

**Existing Physics:**
- Higgs and Top Quark

- Learn “everything” about H (125)
- Probe dynamics of EWSB

**New Physics beyond SM:**
- Direct or indirect DM searches
- Evidence for BSM physics
- Hints of a new mass scale

**Production xsects.**

**ILC timetable**

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
<th>2060</th>
<th>2070</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILC</td>
<td>preparation</td>
<td>250GeV</td>
<td>370GeV</td>
<td>500GeV</td>
<td>High Luminosity</td>
<td>1 TeV</td>
<td>several TeV, upgrade</td>
</tr>
<tr>
<td></td>
<td>construction</td>
<td>2018</td>
<td>2028</td>
<td>2034</td>
<td>2040</td>
<td>2048</td>
<td></td>
</tr>
</tbody>
</table>
The International Linear Collider (ILC)

**Polarised electron source**

**Polarised positron source**

**Damping Rings**

**Ring to Main Linac (RTML)**

(inc. bunch compressors)

*P(e-,e+)=(-0.8,+0.3) @ 250 - 500 GeV*

*P(e-,e+)=(0.8,+0.2) @ 1 TeV*

Almost doubles luminosity for Hγγ events

*ILD*  

*SiD*

- Japanese Mountainous Sites -

**TDR finished June 2013**

The Compact Linear Collider (CLIC)

Envisioned lower bound on CoM is now 350 GeV

80% $e^-$ polarisation foreseen at CLIC → 12% more HZ and $He^+e^-$ events → 80% more $H

S. Gascon-Shotkin 'Future Prospects for BEHGK Bosons', OAC Kolymbari, Crete, July 30 2014
The Future Circular Collider (FCC)

- pp collider (FCC-hh, protons or ions) – 50 TeV* – defines infrastructure.
- e-p option (FCC-eh)
- Organized as an international collaboration, Infrastructure in Geneva area
  * Beam energy

**LEGEND**
- LHC tunnel
- HE_LHC 80km option
- potential shaft location

**Aim for CDR/Cost Review for next ESG (2018)**

Future e+e- CepC/ Future pp SppC

- Beam energies: CepC 120 GeV, SppC 32 TeV
- Aims for CDR end of 2014, e+e- collisions ~2028; pp collisions ~2042

CepC, SppC

CEPC-SppC Layout

CEPC Reference: ILD-like detector
Higgs boson production at future pp Colliders

- $tt\bar{t}h$ overtakes VH in importance at CoM of $\sim 40$ TeV
- Production of a 2$^{nd}$ heavy Higgs boson at CoM of 100 TeV
- H$^+$/- coproduction with $tb$ 2 orders of magnitude higher at 100 than at 14 TeV CoM
e+e-HZZ coupling and related measurements

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

Inclusive H decay

Exclusive H decay modes

S. Watanuki @ LCWS13, H. Li, et. al, arXiv:1202.1439

CLIC

ILC

FCC-ee

E. Sicking, ICHEP14

M. Ruan, ICHEP14

S. Gascon-Shotkin "Future Prospects for BEHIGK Bosons", OAC Kolymbari, Crete, July 30 2014
e+e- HWW couplings

@1 TeV

$Y_2 = \sigma_{\nu\nu H} \cdot \text{Br}(H \to b\bar{b}) \propto g_{HWW}^2 \cdot \text{Br}(H \to b\bar{b})$

$Y_3 = \sigma_{ZH} \cdot \text{Br}(H \to b\bar{b}) \propto g_{HZZ}^2 \cdot \text{Br}(H \to b\bar{b})$

$g_{HWW} \propto \sqrt{\frac{Y_2}{Y_3}} \cdot g_{HZZ} \propto \sqrt{\frac{Y_1 Y_2}{Y_3}}$


△g_{HWW} is actually the limit to all other couplings precisions except g_{HZZ}.

CLIC uses flavor tagging to separate different hadronic final states of H decay

Future Top Yukawa Coupling via ttbarH

- Largest Yukawa coupling.
- Cross section significantly enhanced from QCD bound state effect at round threshold.
- Counting experiment, $\sigma_{ttH} \propto g_{Htt}^2$.
- Direct measurement of $g_{Htt}$.
- Multi-jets final states, detector benchmark analyses.

<table>
<thead>
<tr>
<th>$\Delta g_{ttH} / g_{ttH}$</th>
<th>500 GeV</th>
<th>+ 1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>14%</td>
<td>3.2%</td>
</tr>
<tr>
<td>LumiUP</td>
<td>7.8%</td>
<td>2%</td>
</tr>
</tbody>
</table>

T. Tanabe, T. Price, et. al, LC-REP-2013-004

Study of $H \to b\bar{b}$ decay and two $t$-decays
Semi-leptonic: $t(\to q\bar{q}b)\bar{t}(\to l\nu\bar{b})H(\to b\bar{b})$
Fully hadronic: $t(\to q\bar{q}b)\bar{t}(\to q\bar{q}b)H(\to b\bar{b})$

Events in 1.5 ab$^{-1}$

Hadronic signal
Other $ttH$
$t\bar{t} \times 0.01$
ttbb
ttZ

$\delta \sigma(ttH)$ vs $\delta \sigma(ttZ)$

<table>
<thead>
<tr>
<th>Energy (TeV)</th>
<th>$\delta \sigma(ttH)$</th>
<th>$\delta \sigma(ttZ)$</th>
<th>$\delta[\sigma(ttH)/\sigma(ttZ)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>$\pm 4.8%$</td>
<td>$\pm 5.3%$</td>
<td>$\pm 0.75%$</td>
</tr>
<tr>
<td>100</td>
<td>$\pm 2.7%$</td>
<td>$\pm 2.3%$</td>
<td>$\pm 0.48%$</td>
</tr>
</tbody>
</table>

Future Higgs Self-Couplings

Sensitivity to HHH coupling

Significant irreducible diagrams effect (interference), $\Delta g/g = F \cdot \Delta \sigma/\sigma$, $F > 0.5$

New weighting method.

Challenging analysis, key is flavor tagging, jet-clustering, etc.


Future Higgs Self-Couplings

Sensitivity to quartic coupling $g_{HHWW}$, 4b final state

Significant irreducible diagrams effect (interference), $\Delta g/g = F \cdot \Delta \sigma/\sigma$, $F > 0.5$

New weighting method.

Challenging analysis, key is flavor tagging, jet-clustering, etc.


Sensitive to HHH coupling

Future Higgs Self-Couplings

Sensitivity to quartic coupling $g_{HHWW}$, 4b final state

Significant irreducible diagrams effect (interference), $\Delta g/g = F \cdot \Delta \sigma/\sigma$, $F > 0.5$

New weighting method.

Challenging analysis, key is flavor tagging, jet-clustering, etc.
## Future Colliders Couplings Summary:

**HL-LHC:** precision factor ~ 2 better than LHC @300 fb-1 (5-10%). First direct observation of couplings to top (ttH) [ILC1000, CLIC competitive] and 2nd generation fermions [CLIC competitive]

**After:** Best precision (few 0.1%) at circular e+e- colliders except for heavy states (ttH and HH) where high CoM energy needed
ILC Type II 2HDM Couplings precision


Fig. 1.5: Higgs mass peak reconstruction in the processes $e^+e^- \rightarrow HA$ (left), and in $e^+e^- \rightarrow H^+H^-$ (right), at a CLIC detector using *model II*, see Section 12.4.3. The corresponding background channels are shown as well. The finite Higgs widths are taken into account.
**FCC-hh BSM Higgs prospects**

- **2HDM: Heavy neutral H → ZZ → 4ℓ (shown) & A → Zh → ℓℓ + {bb, tt}**
- **σ x BR sensitivity to 100s of fb**
- **5σ discovery contour in the tanβ-cos(β–α) plane**

*Graphs showing 5σ signal significance and 95% CL exclusion.*

*N. Craig et al, BSM@100 TeV (Feb 2014)*

*Type 1 and Type 2 2HDM plots showing LHC H → ZZ vs. couplings, m_H = 800 GeV.*
The future lepton and hadron colliders currently under consideration offer complementarity in the possibilities for precision measurements of the newly-discovered Higgs boson, as well as significant capabilities for exploration of the space still left open for the discovery of additional Higgs bosons in a context beyond the Standard Model. An exciting road lies before us!
Acknowledgements

Thanks to:


And of course the workshop organisers and sponsors ....:

Related talks to come:

ROSZKOWSKI, NIKOLAIDOU, MOHAMMADI, DJOUADI, SAVIN, GARAY WALLS, NIKOLOPOULOUS, HAGEBOECK, BASYE, TSUKERMAN, MANKEL, GORI, TORRES, TREILLE, PAUSS, KORATZINOS (CERN 60th Anniversary), LEVY, LEBEDEV, SHIMOTANI, PASECHNIK, VLACHOS, HOEPFNER, ALEXOPOULOS, LATINA, RADOS, BELUFFI, GODBOLE

Thank you!
## ATLAS

### Signal Strength Precision Details

<table>
<thead>
<tr>
<th>$\Delta \mu/\mu$</th>
<th>300 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All unc.</td>
<td>No theory unc.</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$ (comb.)</td>
<td>0.39</td>
<td>0.38</td>
</tr>
<tr>
<td>(incl.)</td>
<td>0.47</td>
<td>0.45</td>
</tr>
<tr>
<td>($tH$-like)</td>
<td>0.73</td>
<td>0.72</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$ (VBF-like)</td>
<td>0.22</td>
<td>0.16</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$ (comb.)</td>
<td>0.12</td>
<td>0.06</td>
</tr>
<tr>
<td>(VH-like)</td>
<td>0.32</td>
<td>0.31</td>
</tr>
<tr>
<td>($tH$-like)</td>
<td>0.46</td>
<td>0.44</td>
</tr>
<tr>
<td>(VBF-like)</td>
<td>0.34</td>
<td>0.31</td>
</tr>
<tr>
<td>(ggF-like)</td>
<td>0.13</td>
<td>0.06</td>
</tr>
<tr>
<td>$H \rightarrow WW$ (comb.)</td>
<td>0.13</td>
<td>0.08</td>
</tr>
<tr>
<td>(VBF-like)</td>
<td>0.21</td>
<td>0.20</td>
</tr>
<tr>
<td>(+1j)</td>
<td>0.36</td>
<td>0.17</td>
</tr>
<tr>
<td>(+0j)</td>
<td>0.20</td>
<td>0.08</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$ (incl.)</td>
<td>1.47</td>
<td>1.45</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ (comb.)</td>
<td>0.14</td>
<td>0.09</td>
</tr>
<tr>
<td>(VH-like)</td>
<td>0.77</td>
<td>0.77</td>
</tr>
<tr>
<td>($tH$-like)</td>
<td>0.55</td>
<td>0.54</td>
</tr>
<tr>
<td>(VBF-like)</td>
<td>0.47</td>
<td>0.43</td>
</tr>
<tr>
<td>(+1j)</td>
<td>0.37</td>
<td>0.14</td>
</tr>
<tr>
<td>(+0j)</td>
<td>0.22</td>
<td>0.12</td>
</tr>
</tbody>
</table>

### CMS: [Scenario2, Scenario1]

<table>
<thead>
<tr>
<th>$L$ (fb$^{-1}$)</th>
<th>$\gamma\gamma$</th>
<th>WW</th>
<th>ZZ</th>
<th>$bb$</th>
<th>$\tau\tau$</th>
<th>$Z\gamma$</th>
<th>$\mu\mu$</th>
<th>inv.</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>[6, 12]</td>
<td>[6, 11]</td>
<td>[7, 11]</td>
<td>[11, 14]</td>
<td>[8, 14]</td>
<td>[62, 62]</td>
<td>[40, 42]</td>
<td>[17, 28]</td>
</tr>
<tr>
<td>3000</td>
<td>[4, 8]</td>
<td>[4, 7]</td>
<td>[4, 7]</td>
<td>[5, 7]</td>
<td>[5, 8]</td>
<td>[20, 24]</td>
<td>[20, 24]</td>
<td>[6, 17]</td>
</tr>
</tbody>
</table>
Global fits targeting the $k$ factors

Assign a modifier to each coupling constant

Do not resolve loops, effective coupling instead ($k_g$, $k_g$ and $k_Zg$)

Results reported in terms of 68% uncertainties (-2DLnL=1) on $k$

$$\sigma \cdot BR(ii \rightarrow H \rightarrow ff) = \sigma_{SM} \cdot BR_{SM} \frac{K_i^2 \cdot K_f^2}{K_H^2}$$
The increase in center-of-mass energy from 8 to 13 or 14 TeV is usually accompanied by a sizeable increase in production cross sections (in general $X^2$ for SM Higgs).

However the LHC experiments will be dealing with greatly increased pileup (number of interactions per beam crossing will go from ~15 to 40).

This will affect the efficiency to identify ‘physics objects’ (electrons, photons, muons, jets…). The experiments are currently reevaluating and reworking the relevant algorithms.

In particular, for analyses searching for relatively low-mass resonances, triggering will be a major challenge.
New LHC / HL-LHC Plan

Run I
- nominal luminosity 75%

Run II
- 25 fb⁻¹
- 0.75 \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- 50 ns bunch
- high pile up ~40
- 50 \(\Rightarrow\) 25 ns

Run III
- 100 fb⁻¹
- 1.5 \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- 25 ns bunch
- pile up ~40

- 300 fb⁻¹
- 1.7-2.2 \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- 25 ns bunch
- pile up ~60

Technical limits (experiments, too) like:

- 5 to 7 x nominal luminosity
- cryolimit interaction regions
- radiation damage

High Luminosity LHC

Technical limits (experiments, too) like:

- 60 ns bunch
- pile up ~60

Run III
- HL-LHC installation
Challenges for low-mass searches in Run 2

The increase in center-of-mass energy from 8 to 13 or 14 TeV is usually accompanied by a sizeable increase in production cross sections (in general $X^2$ for SM Higgs).

However the LHC experiments will be dealing with greatly increased pileup (number of interactions per beam crossing will go from ~15 to 40). This will affect the efficiency to identify 'physics objects' (electrons, photons, muons, jets...). The experiments are currently reevaluating and reworking the relevant algorithms.

In particular, for analyses searching for relatively low-mass resonances, triggering will be a major challenge.

S. Gascon-Shotkin ‘After the Discovery’ Benasque April 10 2014

Is it really possible to go so high?

Looking at performance offered by practical SC, considering tunnel size and basic engineering (forces, stresses, energy) the practical limits is around 20 T. Such a challenge is similar to a 40 T solenoid ($\mu$-C)
### Precisions of absolute Higgs couplings @ ILC

*model independent global fit*

<table>
<thead>
<tr>
<th>coupling</th>
<th>Baseline</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Δg/g</td>
<td>250 GeV</td>
<td>+ 500 GeV</td>
<td>+ 1 TeV</td>
</tr>
<tr>
<td>HZZ</td>
<td>1.3%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>HWW</td>
<td>4.8%</td>
<td>1.2%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Hbb</td>
<td>5.3%</td>
<td>1.6%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Hcc</td>
<td>6.8%</td>
<td>2.8%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Hgg</td>
<td>6.4%</td>
<td>2.3%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Hττ</td>
<td>5.7%</td>
<td>2.3%</td>
<td>1.7%</td>
</tr>
<tr>
<td>Hγγ</td>
<td>18%</td>
<td>8.4%</td>
<td>4%</td>
</tr>
<tr>
<td>Hμμ</td>
<td>-</td>
<td>-</td>
<td>16%</td>
</tr>
<tr>
<td>Htt</td>
<td>-</td>
<td>14%</td>
<td>3.1%</td>
</tr>
<tr>
<td>Γ</td>
<td>11%</td>
<td>5%</td>
<td>4.6%</td>
</tr>
<tr>
<td>Br(Inv)</td>
<td>&lt;0.95%</td>
<td>&lt;0.95%</td>
<td>&lt;0.95%</td>
</tr>
<tr>
<td>HHH</td>
<td>-</td>
<td>83%</td>
<td>21%</td>
</tr>
</tbody>
</table>

## Summary of observables @ ILC

<table>
<thead>
<tr>
<th>Baseline</th>
<th>mH = 125 GeV</th>
<th>ILD &amp; SiD: DBD</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 GeV: 250 fb^{-1}</td>
<td>P(e^{-},e^{+})=(-0.8, +0.3) @ 250, 500 GeV</td>
<td>P(e^{-},e^{+})=(-0.8, +0.2) @ 1 TeV</td>
</tr>
<tr>
<td>500 GeV: 500 fb^{-1}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 TeV: 1000 fb^{-1}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>@ 250 GeV</th>
<th>@ 500 GeV</th>
<th>@ 1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECM</td>
<td>ZH</td>
<td>vvH(fusion)</td>
<td>ZH</td>
</tr>
<tr>
<td>luminosity · fb</td>
<td>250</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>polarization (e^{-},e^{+})</td>
<td>(-0.8, +0.3)</td>
<td>(-0.8, +0.3)</td>
<td>(-0.8, +0.2)</td>
</tr>
<tr>
<td>process</td>
<td>2.6%</td>
<td>-</td>
<td>3.0%</td>
</tr>
<tr>
<td>cross section</td>
<td>σ·Br</td>
<td>σ·Br</td>
<td>σ·Br</td>
</tr>
<tr>
<td>H→bb</td>
<td>1.2%</td>
<td>10.5%</td>
<td>1.8%</td>
</tr>
<tr>
<td>H→cc</td>
<td>8.3%</td>
<td>13%</td>
<td>6.2%</td>
</tr>
<tr>
<td>H→gg</td>
<td>7%</td>
<td>11%</td>
<td>4.1%</td>
</tr>
<tr>
<td>H→WW^{*}</td>
<td>6.4%</td>
<td>9.2%</td>
<td>2.4%</td>
</tr>
<tr>
<td>H→ττ</td>
<td>4.2%</td>
<td>5.4%</td>
<td>9%</td>
</tr>
<tr>
<td>H→ZZ^{*}</td>
<td>19%</td>
<td>25%</td>
<td>8.2%</td>
</tr>
<tr>
<td>H→γγ</td>
<td>29-38%</td>
<td>29-38%</td>
<td>20-26%</td>
</tr>
<tr>
<td>H→μμ</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ttH, H→bb</td>
<td>-</td>
<td>-</td>
<td>28%</td>
</tr>
<tr>
<td>H→Inv. (95% C.L.)</td>
<td>&lt; 0.95%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

---

being updated by new studies with mH = 125 GeV

S. Gascon-Shotkin ‘After the Discovery’ Benasque April 10 2014
From observables to couplings — Global Fit

\[ \chi^2 = \sum_{i=1}^{35} \left( \frac{Y_i - Y_i'}{\Delta Y_i} \right) \]

\[ Y_i' = F_i \cdot \frac{g^2_H A_i A_i \cdot g^2_H B_i B_i}{\Gamma_0} \]

\( A_i = Z, W, t \)

\( B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay} \)

\[ (i = 1, \cdots, 33) \]

\[ F_i = S_i G_i \]

\[ S_i = \left( \frac{\sigma_{ZH}}{g^2_{HZZ}} \right), \left( \frac{\sigma_{v\bar{v}H}}{g^2_{HWW}} \right), \text{ or } \left( \frac{\sigma_{t\bar{t}H}}{g^2_{Htt}} \right) \]

\[ G_i = \left( \frac{\Gamma_i}{g^2_i} \right) \]

- It is the recoil mass measurement that is the key to unlock the door to this completely model-independent analysis!
- Cross section calculations \((S_i)\) do not involve QCD ISR.
- Partial width calculations \((G_i)\) do not need quark mass as input.

\[ \star \text{ theoretical calculations of Higgs particle widths are now at O}(1\%), \text{ and are expected to achieve per-mille level in next decade!} \ (\text{M.Peskin, et. al, arXiv:1404.0319}) \]

**Systematic Errors**

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>LumUp</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity</td>
<td>0.1%</td>
<td>0.05%</td>
</tr>
<tr>
<td>polarization</td>
<td>0.1%</td>
<td>0.05%</td>
</tr>
<tr>
<td>b-tag efficiency</td>
<td>0.3%</td>
<td>0.15%</td>
</tr>
</tbody>
</table>
Work pages: ILC

$g(hAA)/g(hAA)_{SM-1}$

LHC/ILC1/ILC/ILCTeV

Coupling to Higgs

ILC ready to go!

ILC Baseline Program

S. Gascon-Shotkin ‘After the Discovery’ Benasque April 10 2014
Work pages: Future ee machines

![Graph showing luminosity vs. $\sqrt{s}$ (GeV)]

Size (km) | $\sqrt{s}$ (GeV) | RF (MV/m) | L per IP ($10^34$) | Bunch/train x-ing rate (Hz) | $\sigma_x$ (μm) | $\sigma_y$ (nm) | Lumi within 1% of $\sqrt{s}$ | Long. polarisation $e^-/e^+$
--- | --- | --- | --- | --- | --- | --- | --- | ---
CEPC | 54 | 240 | 20 | 1.8 | $4\times10^5$ | 74 | 160 | >99% | considered
FCC-ee | 100 | 240 | 20 | 6 | $2\times10^7$ | 22 | 45 | >99% | considered
ILC | 31 | 250 | 14.7 | 0.75 | 5 | 0.7 | 7.7 | 87% | 80%/30%
ILC | 31 | 500 | 31.5 | 1.8 | 5 | 0.5 | 5.9 | 58% | 80%/30%
CLIC | 48 | 3000 | 100 | 6 | 50 | 0.04 | 1 | 33% | 80%/considered


S. Gascon-Shotkin ‘After the Discovery’ Benasque April 10 2014
Integrated luminosities correspond to 3-5 years of running at each $\sqrt{s}$ for $e^+e^-$ and 5 years with 2 experiments for $pp\rightarrow tt\gamma\gamma$, $tt4l\rightarrow bb\gamma\gamma$.

<table>
<thead>
<tr>
<th></th>
<th>$\sqrt{s}$ (TeV)</th>
<th>$L$ (ab$^{-1}$)</th>
<th>$N_H$ (10$^6$)</th>
<th>$N_{ttH}$</th>
<th>$N_{HH}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC-ee*</td>
<td>0.24+0.35</td>
<td>10</td>
<td>2</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>ILC</td>
<td>0.25+0.5</td>
<td>0.75</td>
<td>0.2</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>ILC-1TeV</td>
<td>0.25+0.5+1</td>
<td>1.75</td>
<td>0.5</td>
<td>3000</td>
<td>400</td>
</tr>
<tr>
<td>CLIC</td>
<td>0.35+1.4+3</td>
<td>3.5</td>
<td>1.5</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>14</td>
<td>3</td>
<td>180</td>
<td>$\rightarrow tt\gamma\gamma$, $tt4l$</td>
<td>$\rightarrow bb\gamma\gamma$</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>100</td>
<td>6</td>
<td>5400</td>
<td>3600 $tt\gamma\gamma$</td>
<td>250 $bb\gamma\gamma$</td>
</tr>
</tbody>
</table>

$^*$ 4 IP

<10% of events usable
Work pages: Future ee couplings comparisons

- Currently studied scenario
  - $\sqrt{s}=350$ GeV/375 GeV, 500 fb$^{-1}$
    - SM Higgs physics including total width measurement
    - Top threshold scan
  - $\sqrt{s}=1.4$ TeV, 1.5 ab$^{-1}$
    - BSM physics
    - $t\bar{t}H$, Higgs self coupling
    - Rare Higgs decays
  - $\sqrt{s}=3$ TeV, 2 ab$^{-1}$
    - BSM physics
    - Higgs self coupling
    - Rare Higgs decays

---

<table>
<thead>
<tr>
<th>SUSY model I</th>
<th>SUSY model II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>State</strong></td>
<td><strong>Mass (GeV)</strong></td>
</tr>
<tr>
<td>Without $\gamma$</td>
<td>A/H</td>
</tr>
<tr>
<td>Without $\gamma$</td>
<td>H$^\pm$</td>
</tr>
<tr>
<td>With $\gamma$</td>
<td>A/H</td>
</tr>
<tr>
<td>With $\gamma$</td>
<td>H$^\pm$</td>
</tr>
</tbody>
</table>

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S. Gascon-Shotkin ‘After the Discovery’ Benasque April 10 2014
Work pages: Future hh machines

<table>
<thead>
<tr>
<th></th>
<th>Ring (km)</th>
<th>Magnets (T)</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>$L \times 10^{34}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LHC</strong></td>
<td>27</td>
<td>8.3</td>
<td>14</td>
<td>up to 5</td>
</tr>
<tr>
<td><strong>HE-LHC</strong></td>
<td>27</td>
<td>16-20</td>
<td>26-33</td>
<td>5</td>
</tr>
<tr>
<td><strong>SppC-1</strong></td>
<td>50</td>
<td>12</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td><strong>SppC-2</strong></td>
<td>70</td>
<td>19</td>
<td>90</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>FCC-hh</strong></td>
<td>100</td>
<td>16</td>
<td>100</td>
<td>$\geq 5$</td>
</tr>
</tbody>
</table>

$\text{Nb}_3\text{Sn}$ ok up to 16 T; HTS needed for 20 T

May reach $\sim 10^{35}$
Work pages: Future hh machines

Comparison of Colliders at the Energy Frontier

Constituent Center-of-Mass Energy [GeV]

Year of First Physics

Hadron colliders

Tevatron

HERA

LEP2

Tristan

PETRA

PEP

ISR

CESR

Spear2

Doris

Spear

Adone

e+e- colliders

VFP-2

ACO

DAFNE

VEP-1

FCC-hh (20T magnets)

HE-LHC (20T magnets)

CLIC 3000

ILC 500

ILC 250-350

CLIC 500

FCC-ee

SppC

CepC

SuperKEKB

KEK-B

PEP-II

S. Gascon-Shotkin ‘After the Discovery’ Benasque April 10 2014
CEPC-SppC Schedule (Preliminary)

• CPEC
  – Pre-study, R&D and preparation work
    • Pre-study: 2013-15 ➔ Pre-CDR by 2014
    • R&D: 2016-2020
    • Engineering Design: 2015-2020
  – Construction: 2021-2027
  – Data taking: 2030-2036

• SPPC
  – Pre-study, R&D and preparation work
    • Pre-study: 2013-2020
    • R&D: 2020-2030
    • Engineering Design: 2030-2035
  – Construction: 2036-2042
  – Data taking: 2042 -
Work pages: Future hh machines

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Work pages: Future hh machines

MSSM

H→TT now

H→TT 14TeV 300/fb

H→TT 14TeV 3000/fb

A→Zh 100TeV

H→ZZ 100TeV

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How precisely do we need to know the Higgs boson?

Effect of New Physics on couplings:

\[ \Delta \kappa / \kappa \sim 5% / \Lambda_{NP}^2 \]  
(\( \Lambda_{NP} \) in TeV)

\[ \rightarrow 0.1-1\% \] precision needed for discovery

### Scenarios with no new particles observable at LHC

<table>
<thead>
<tr>
<th>Scenario</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 -3% )</td>
</tr>
</tbody>
</table>

Integrating luminosities correspond to 3-5 years of running at each \( \sqrt{s} \) for e+e− and 5 years with 2 experiments for pp

<table>
<thead>
<tr>
<th>Scenario</th>
<th>( \sqrt{s} ) (TeV)</th>
<th>( L ) (ab⁻¹)</th>
<th>( N_H ) (10⁶)</th>
<th>( N_{ttH} )</th>
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<td>14</td>
<td>3</td>
<td>180</td>
<td>3600, ttYY</td>
<td>250</td>
</tr>
<tr>
<td><strong>FCC-hh</strong></td>
<td>100</td>
<td>6</td>
<td>5400</td>
<td>12000, ttYY</td>
<td>20000</td>
</tr>
</tbody>
</table>

* 4 IP

<10% of events usable
F. Gianotti, LHCP 2014, 6/6/2014

- LHC: ~20% today → 5-10% in ~2020 (14 TeV, 300 fb⁻¹)
- HL-LHC:
  - factor ~ 2 better than LHC @300 fb⁻¹
  - first direct observation of couplings to top (ttH) and 2nd generation fermions (H → μμ)
  - model dependent measurements: Γ_H and σ(H) from SM
- e⁺e⁻:
  - model-independent: σ(HZ) and Γ_H from data: ZH → μμX recoil mass (σ, Γ_H), Hvv → bbvv (Γ_Z)
  - all decay modes accessible (fully hadronic, invisible, exotic)
- Best precision (few 0.1%) at circular colliders (luminosity !), except for heavy states (ttH and HH) where high energy (linear colliders, FCC-hh) needed

Note: theory uncertainties, e.g. presently O(1%) on BR, need to be improved to match expected superb experimental precision and sensitivity to new physics.

<table>
<thead>
<tr>
<th>Coupling</th>
<th>HL-LHC</th>
<th>FCC-ee</th>
<th>ILC (500)</th>
<th>ILC (1000)</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Js → Int. L →</td>
<td>14000 6000</td>
<td>240 +350 10000+2600</td>
<td>250+500 250+500</td>
<td>250+500+1000 250+500+1000</td>
<td>350+1400+3000 500+1500+2000</td>
</tr>
<tr>
<td>K_W</td>
<td>2-5%</td>
<td>0.19%</td>
<td>1.2%</td>
<td>1.2%</td>
<td>2.1%</td>
</tr>
<tr>
<td>K_Z</td>
<td>2-4%</td>
<td>0.15%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>2.1%</td>
</tr>
<tr>
<td>K_g</td>
<td>3-5%</td>
<td>0.80%</td>
<td>2.3%</td>
<td>1.6%</td>
<td>2.2%</td>
</tr>
<tr>
<td>K_μ</td>
<td>2-5%</td>
<td>1.5%</td>
<td>8.4%</td>
<td>4.0%</td>
<td>&lt;5.9%</td>
</tr>
<tr>
<td>K_ν</td>
<td>~7%</td>
<td>6.2%</td>
<td>--</td>
<td>16%</td>
<td>5.6%</td>
</tr>
<tr>
<td>K_c</td>
<td>--</td>
<td>0.71%</td>
<td>2.8%</td>
<td>1.8%</td>
<td>2.2%</td>
</tr>
<tr>
<td>K_T</td>
<td>2-5%</td>
<td>0.54%</td>
<td>2.4%</td>
<td>1.8%</td>
<td>&lt;2.5%</td>
</tr>
<tr>
<td>K_b</td>
<td>4-7%</td>
<td>0.42%</td>
<td>1.7%</td>
<td>1.3%</td>
<td>2.1%</td>
</tr>
<tr>
<td>BR_invis</td>
<td>&lt;10%</td>
<td>&lt;0.19%</td>
<td>&lt;0.9%</td>
<td>&lt;0.9%</td>
<td>na</td>
</tr>
<tr>
<td>K_μ</td>
<td>~5%</td>
<td>13%indirect</td>
<td>14%</td>
<td>3.2%</td>
<td>&lt;4.5%</td>
</tr>
<tr>
<td>K_HH (self)</td>
<td>?</td>
<td>--</td>
<td>--</td>
<td>26% (13% ultimate)</td>
<td>10%</td>
</tr>
</tbody>
</table>

Rare decays → HL-LHC is competitive

FCC-hh: K_μ: few percent ?? K_HH ~ 8%
Regardless of the detailed scenario, and even in the absence of theoretical/experimental preference for a specific $E$ scale, the directions for future high-E colliders are clear:

- **highest precision** → to probe $E$ scales potentially up to $O(100)$ TeV and smallest couplings
- **highest energy** → to explore directly new territories and get crucial information to interpret results from indirect probes

LHC Run-2 and beyond may (hopefully !) bring additional no-lose theorems:

- if new (heavy) physics is discovered
  - completion of spectrum and detailed measurements of new physics likely require multi-TeV energies
- if indications emerge for the scale of new physics in the 10-100 TeV region
  - (e.g. from dijet angular distributions → $\Lambda$ compositeness)
  - need the highest-energy pp collider to probe directly the scale of new physics