Higgs Coupling Measurements

Status, prospects, and interplay with searches for physics BSM
Introduction

- Fantastic progress since **discovery July 2012**
  - Observation in three boson channels
  - Evidence for fermion couplings
  - Precision mass measurement ~126 GeV
  - Spin determined
- **Looks more and more like the SM Higgs boson**
  - No evidence for non-SM decays
  - No evidence for additional Higgs bosons
- ATLAS and CMS are finalizing final Run I papers and are preparing combinations

arXiv:1312.5353

ATLAS-CONF-2013-012
Is there BSM physics hidden in the “Higgs sector”?

Experimental post-discovery approach

- Measure (126 GeV) Higgs properties
- Search for additional Higgs bosons
- Search for BSM in signatures with Higgs bosons
- Search for BSM Higgs decays
Introduction

- Gateways to BSM physics in the 126 GeV Higgs
  - Mixing
  - Loops
  - Decays

- In general BSM physics modifies absolute value and tensor structure
  - we factorize the problem, knowing that this is incorrect
Higgs coupling measurements
Coupling Measurements

- **Strategy:** narrow width approximation

\[(\sigma \cdot \text{BR}) (ii \to H \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}\]

- **Measurement:** parametrize deviations wrt SM in production and decay
  - implies precise knowledge of the SM prediction
  - BSM acceptance effects are not considered

\[\Delta_x \equiv \frac{g_x^{\text{SM}}}{g_x} - 1\]

\[\kappa_x \equiv \frac{g_x^{\text{SM}}}{g_x}\]
LHC Higgs production and decay

\( m_H = 125 \text{ GeV, 8 TeV} \)

<table>
<thead>
<tr>
<th>Process</th>
<th>Diagram</th>
<th>Cross section [fb]</th>
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<table>
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<tr>
<td>( \tau \tau )</td>
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<td>cc</td>
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<tr>
<td>( \mu \mu )</td>
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<tr>
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<tr>
<td>gg</td>
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<td>ZZ</td>
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<td>( \gamma \gamma )</td>
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<tr>
<td>( Z\gamma )</td>
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<tr>
<td>( \Gamma_H ) [MeV]</td>
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\( m_H = 125 \text{ GeV} \)

\( m_{H^0} = 125 \text{ GeV} \)
## Available Channels

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<tr>
<th>Higgs Decay</th>
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<th>VBF</th>
<th>VH</th>
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<td>$H \rightarrow \gamma\gamma$</td>
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<td>$H \rightarrow WW \rightarrow 2l2\nu$</td>
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<tr>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
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<td>$H \rightarrow Z\gamma$</td>
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<td>$H \rightarrow \mu\mu$</td>
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<tr>
<td>$H \rightarrow$ invisible</td>
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<td>blue</td>
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</table>

`simplified view`
Cross Contamination

\[
\eta_{s}^{c,f} = \sum_{i} (\sigma^{i} \times B^{f})_{SM} \times A_{i}^{c,f} \times \epsilon_{i}^{c,f} \times \mathcal{L} \times \frac{\kappa_{i} \cdot \kappa_{f}}{\kappa_{H}^{2}}
\]
Total Width

- SM Higgs total width $\Gamma_H \approx 4.2$ MeV
- Indirect constrained in coupling fits
  - requires further assumptions
    \[ \kappa_H^2 \equiv \frac{\Gamma_H}{\Gamma_{SM}} \]
    \[ \kappa_H^2 = \sum_f \kappa_f^2 \frac{B_{SM}(H \rightarrow ff)}{1 - B_{BSM}} \]

- Measurements at the LHC
  - interference between Higgs signal $gg \rightarrow H \rightarrow \gamma\gamma$ and continuum $gg \rightarrow \gamma\gamma$ results in Higgs mass shift
  - off-shell $H^*$ production in $H^* \rightarrow ZZ^{(*)}$ (more later)
Probing BSM

• Simultaneous fit of all couplings with several assumptions on total width

• Searches for new physics in loops: $k_g, k_\gamma, BR_{BSM}$

• Fermion vs vector boson couplings: $k_V, k_f$

• Search for asymmetries: $\lambda_{WZ}, \lambda_{du}, \lambda_{lq}$

• Overall scaling of signal strength: $\mu$
Effective Field Theory Approach

- Parametrize SM deviation by higher-dimensional operators

\[ \mathcal{L}_{\text{eff}} = \sum_{n} \frac{f_n}{\Lambda^2} \mathcal{O}_n \]

- Allows study of large class of BSM models

- Allows combination with electroweak precision data

- Does not account for effects of light particles in loops, but theses can be studied with specific BSM models

- No results from LHC experiments for now.
Experimental Status

Current Player

Future Player

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<tr>
<th>Facility</th>
<th>HL-LHC</th>
<th>ILC</th>
<th>ILC(LumiUp)</th>
<th>CLIC</th>
<th>TLEP (4 IPs)</th>
<th>HE-LHC</th>
<th>VLHC</th>
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<td>350/1400/3000</td>
<td>240/350</td>
<td>33,000</td>
<td>100,000</td>
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<td>250+500+1000</td>
<td>1150+1600+2500</td>
<td>500+1500+2000</td>
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<td>$\int dt$ ($10^7$s)</td>
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<td>3+3+3</td>
<td>(ILC 3+3+3) + 3+3+3</td>
<td>3.1+4+3.3</td>
<td>5+5</td>
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### Status of LHC Higgs program

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<tr>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>4.6+20.7</td>
<td>5.1+19.6</td>
<td>mass, discovery, spin/parity</td>
<td>4 leptons</td>
<td>6.6 (4.4)</td>
<td>124.3 ±0.6 (stat) ±0.5 (sys)</td>
<td>1.7+0.5-0.4</td>
<td>✓</td>
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<tr>
<td></td>
<td>ATLAS-CONF-2013-012</td>
<td>arXiv: 1312.5353</td>
<td></td>
<td></td>
<td>6.8 (6.7)</td>
<td>125.6 ±0.4 (stat) ±0.2 (sys)</td>
<td>0.93+0.29-0.25</td>
<td>✓</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow 2l2\nu$</td>
<td>4.6+20.7</td>
<td>4.9+19.5</td>
<td>cross section, coupling</td>
<td>2 leptons, MET</td>
<td>3.8 (3.7)</td>
<td>consistent</td>
<td>1.01 ± 0.31</td>
<td>✓</td>
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<tr>
<td></td>
<td>ATLAS-CONF-2013-030</td>
<td>arXiv: 1312.1129</td>
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<td>4.3 (5.8)</td>
<td>125 ± 4</td>
<td>0.72+0.20-0.18</td>
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<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>4.8+20.7</td>
<td>5.1+19.6</td>
<td>mass, discovery, couplings</td>
<td>two photons</td>
<td>7.4 (4.3)</td>
<td>126.8 ±0.2 (stat) ±0.7 (sys)</td>
<td>1.65+0.33-0.28</td>
<td>✓</td>
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<tr>
<td></td>
<td>ATLAS-CONF-2013-012</td>
<td>CMS-PAS-HIG-13-001</td>
<td></td>
<td></td>
<td>3.2 (4.2)</td>
<td>125.4 ±0.5 (stat) ±0.6 (sys)</td>
<td>0.78+0.28-0.26</td>
<td>✓</td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>4.7+20.3</td>
<td>5.0+18.9</td>
<td>total width, coupling to fermions</td>
<td>two b-jets</td>
<td>-</td>
<td>consistent</td>
<td>0.2 ± 0.7</td>
<td>-</td>
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<tr>
<td></td>
<td>ATLAS-CONF-2013-079</td>
<td>arXiv: 1310.3687</td>
<td></td>
<td></td>
<td>2.1 (2.1)</td>
<td>consistent</td>
<td>1.0 ± 0.5</td>
<td>-</td>
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<tr>
<td>$H \rightarrow t\bar{t}$</td>
<td>20.3</td>
<td>4.9+19.4</td>
<td>couplings to leptons</td>
<td>hadronic taus, leptons, MET</td>
<td>4.1 (3.2)</td>
<td>-</td>
<td>1.4 ± 0.5 - 0.4</td>
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<tr>
<td></td>
<td>ATLAS-CONF-2013-108</td>
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<td>3.4 (3.6)</td>
<td>122 ± 7</td>
<td>0.78 ± 0.27</td>
<td>-</td>
</tr>
</tbody>
</table>
Tevatron

- $p$-value $3.0\sigma$ ($1.9\sigma$ expected) at $m_H = 125$ GeV
- Measurement of $H \rightarrow bb$ competitive with LHC
Progress on ttH

Direct study of top Yukawa coupling

CMS exploring all accessible Higgs decay modes

Full program on ttH underway in ATLAS

Approaching SM sensitivity in 8 TeV data
Coupling Results

• CMS coupling fits (HIG-13-005) based on preliminary results released Moriond’13. Updated analyses are available.

• ATLAS coupling fits (ATLAS-CONF-2014-009) based on preliminary results released Moriond’14

• Tevatron results published in Phys.Rev.D88,052014
Summary of Signal Strength

**ATLAS Prelim.**

<table>
<thead>
<tr>
<th>Process</th>
<th>$\mu$ (stat.)</th>
<th>Total uncertainty</th>
<th>$\pm 1\sigma$ on $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>1.57$^{+0.33}_{-0.28}$</td>
<td>$\pm 1\sigma$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4l$</td>
<td>1.44$^{+0.40}_{-0.35}$</td>
<td>$\pm 1\sigma$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow l\nu$</td>
<td>1.00$^{+0.32}_{-0.29}$</td>
<td>$\pm 1\sigma$</td>
<td></td>
</tr>
<tr>
<td>Combined $H \rightarrow \gamma\gamma$, $ZZ^<em>$, $WW^</em>$</td>
<td>1.35$^{+0.21}_{-0.13}$</td>
<td>$\pm 1\sigma$</td>
<td></td>
</tr>
<tr>
<td>$W, Z H \rightarrow b\bar{b}$</td>
<td>0.2$^{+0.7}_{-0.6}$</td>
<td>$\pm 1\sigma$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$ (8 TeV data only)</td>
<td>1.4$^{+0.5}_{-0.4}$</td>
<td>$\pm 1\sigma$</td>
<td></td>
</tr>
<tr>
<td>Combined $H \rightarrow b\bar{b}$, $\tau\tau$</td>
<td>1.09$^{+0.36}_{-0.32}$</td>
<td>$\pm 1\sigma$</td>
<td></td>
</tr>
</tbody>
</table>

**Combined**

$\mu = 1.44^{+0.59}_{-0.56}$
Vector and fermion coupling
Fermion Coupling Asymmetry

- BSM models (e.g. 2HDM) show asymmetries between up and down type or lepton and quark couplings
- Three parameter fits
- Measurement of $\kappa_b$ and $\kappa_\tau$ coupling allows measurement of $\lambda_{du}$
- Measurement of $\kappa_\tau$ allows a measurement of $\lambda_{lq}$
- Downtype fermion couplings established by ATLAS ($\sim3.6\sigma$) and CMS ($\sim4.0\sigma$)
Lepton Quarks Asymmetry

- BSM models (e.g. 2HDM) show asymmetries between up and down type or lepton and quark couplings
- Three parameter fits
- Measurement of $\kappa_b$ and $\kappa_\tau$ coupling allows measurement of $\lambda_{du}$
- Measurement of $\kappa_\tau$ allows a measurement of $\lambda_{lq}$
- Downtype fermion couplings established by ATLAS ($\sim 3.6\sigma$) and CMS ($\sim 4.0\sigma$)
Probing BSM in Loops

• Effective couplings to gluons and photons
Probing BSM in Loops

- Constrain total width assuming SM Higgs tree-level couplings
- Degeneracy of $\text{BR}_{\text{BSM}}$ with gluon coupling from $\sigma(gg\rightarrow H)$
- Direct search for invisible Higgs decays or total width measurements not included

CMS: $\mathcal{B}_{\text{BSM}} < 0.52$ (0.58 expected) at 95% CL
ATLAS: $\mathcal{B}_{\text{BSM}} < 0.42$ (0.55 expected) at 95% CL
Invisible Higgs Decays

- Direct search for invisible Higgs decays
- VBF and ZH production modes used so far
- Gluon fusion production accessible
- DM interpretation complementary to direct searches

ATLAS (H → invisible): $B_{inv} < 0.75$ (0.62 expected) at 95% CL

CMS (H → invisible): $B_{inv} < 0.58$ (0.44 expected) at 95% CL

arXiv:1404.1344
Generic Fits
Generic Fits

\[ g_x = g_x^{SM} \left(1 + \Delta_x\right) \]
Rare SM Decay Channels

\[ H \rightarrow Z\gamma \]

\[ H \rightarrow \gamma^*\gamma \rightarrow \mu^+\mu^-\gamma \]

- Rare SM decay channels can be added to the general coupling fit
- No direct effect on other couplings, but other channel constrain production modes
Rare SM Decay Channels

- $\text{BR}_{\text{SM}} (H \rightarrow \mu\mu) = 2.2 \times 10^{-4}$
- Good resolution, signal tiny, huge background
- Testing 2nd generation Higgs coupling

---

ATLAS (H $\rightarrow \mu\mu$): $\mu < 9.8$ (8.2 expected)

CMS (H $\rightarrow \mu\mu$): $\mu < 7.4$ (5.1 expected)

ATLAS Preliminary

CMS Preliminary

ATLAS-CONF-2013-010

CMS-HIG-13-007
Total Width Measurement

- Enhancement of cross section at high mass due to Higgs. ~8% in ZZ final state

- Used to constrain $\Gamma_H$

$$r = \frac{\Gamma_H}{\Gamma_H^{SM}}$$

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} = \frac{\kappa_Z^2}{r} \frac{(\sigma \cdot B)^{SM}}{r} \equiv \mu (\sigma \cdot B)^{SM}$$

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm_{ZZ}^2} \propto g_{ggH}^2 g_{ZZ}^2 \frac{F(m_{ZZ})}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

$$\frac{d\sigma_{\text{off-peak}}^{off-peak,SM}}{dm_{ZZ}} = \kappa_Z^2 \frac{d\sigma_{\text{off-peak,SM}}^{off-peak,SM}}{dm_{ZZ}} = \mu r \frac{d\sigma_{gg\to H\to ZZ}}{dm_{ZZ}}$$

J. Cambell et al, arXiv:1311.3589
Total Width Measurement

- Experimental constraint on Higgs total width using $H^* \rightarrow ZZ$
- Combination of 4l and 2l2v final states
- Results:
  - $r < 4.2$ (8.5 expected) @ 95% CL
  - $\Gamma_H < 17$ MeV (35 MeV expected) @ 95% CL
Prospects at the HL-LHC and beyond

8 TeV
0.7x10^{34} \text{cm}^{-2}\text{s}^{-1}

13-14 TeV
2014 | 2015 | 2016 | 2017
1x10^{34} \text{cm}^{-2}\text{s}^{-1}

HL-LHC
2022 | 2023 | **2024**
5x10^{34} \text{cm}^{-2}\text{s}^{-1}
General Coupling Fits

\( \kappa_g, \kappa_Y, \kappa_{Z\gamma} \): loop diagrams \( \rightarrow \) allow potential new physics
\( \kappa_W, \kappa_Z \): vector bosons
\( \kappa_t, \kappa_b \): up- and down-type quarks
\( \kappa_{\tau}, \kappa_{\mu} \): charged leptons

total width from sum of partial widths

Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: \( \Delta \text{theory} / 2 \), rest \( \propto 1/\sqrt{L} \)

coupling precision 2-10 %
factor of \(~2\) improvement from HL-LHC

**Table:**

<table>
<thead>
<tr>
<th>( L (fb^{-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>
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<td>[10,12]</td>
<td>[8,8]</td>
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**Figure:** CMS Projection

**Text:** arXiv:1307.7135
Theoretical Uncertainties

- To test the importance of theoretical uncertainties we show the effect of removing them.

- Theoretical uncertainties dominated by QCD scale and PDF uncertainties. Uncertainty on BR become relevant at few % precision.

\[ \Delta \text{theory} = 0, \text{rest unchanged} \]

\[ \text{arXiv:1310.8361} \]
Comparison of ATLAS and CMS prospects

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<th>( \kappa_b )</th>
<th>( \kappa_t )</th>
<th>( \kappa_\tau )</th>
<th>( \kappa_{Z\gamma} )</th>
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<td>[7,10]</td>
<td>[2,5]</td>
<td>[10,12]</td>
<td>[8,8]</td>
</tr>
</tbody>
</table>

Large differences in fits for coupling strength
• ATLAS connects \( \kappa_\tau \) with \( \kappa_b \) to overcome \( H \rightarrow b\bar{b} \) mode, but \( H \rightarrow \tau\tau \) then becomes overall limitation in constraining total width.

\[ \kappa_H^2 = \sum_X \kappa_X^2 \text{BR}_{SM}(H \rightarrow X) \]
Higgs Couplings at Lepton Collider

- Higgs-strahlung allows decay mode independent measurement
  - performed on OPAL data
  - benchmark for lepton collider studies

- Couplings
  - model independent extraction of $g_{ZZH}$ from $\sigma_{ZH}$ in fit to recoil mass spectrum
  - other Higgs couplings extracted from $\sigma_{ZH} \times \text{BR}$ measurements and $g_{ZZH}$
  - total width extracted from combination of initial and final state measurements
  - precision limited by statistics
Potential Future Facilities

Future Circular Collider (FCC)

CLIC

ILC

Neutrino Factory

Muon Collider
Potential Future Facilities

<table>
<thead>
<tr>
<th>LHC 100/fb</th>
<th>LHC 300/fb</th>
<th>LHC 3/ab</th>
<th>ILC 250-500GeV</th>
<th>ILC 1TeV</th>
<th>CLIC &gt;1TeV</th>
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<td>TDR</td>
<td>LOI</td>
<td>TDR</td>
<td>TDR</td>
<td>CDR</td>
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</table>

from Chip Brock
# Higgs Couplings at Lepton Collider

<table>
<thead>
<tr>
<th>Facility</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC500</th>
<th>ILC500-up</th>
<th>ILC1000</th>
<th>ILC1000-up</th>
<th>CLIC</th>
<th>TLEP (4 IPs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>14,000</td>
<td>14,000</td>
<td>250/500</td>
<td>250/500</td>
<td>250/500/1000</td>
<td>250/500/1000</td>
<td>350/1400/3000</td>
<td>240/350</td>
</tr>
<tr>
<td>$\int \mathcal{L} dt$ (fb$^{-1}$)</td>
<td>300/expt</td>
<td>3000/expt</td>
<td>250+500</td>
<td>1150+1600</td>
<td>250+500+1000</td>
<td>1150+1600+2500</td>
<td>500+1500+2000</td>
<td>10,000+2600</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>5 – 7%</td>
<td>2 – 5%</td>
<td>8.3%</td>
<td>4.4%</td>
<td>3.8%</td>
<td>2.3%</td>
<td>–/5.5/&lt;5.5%</td>
<td>1.45%</td>
</tr>
<tr>
<td>$\kappa_\eta$</td>
<td>6 – 8%</td>
<td>3 – 5%</td>
<td>2.0%</td>
<td>1.1%</td>
<td>1.1%</td>
<td>0.67%</td>
<td>3.6/0.79/0.56%</td>
<td>0.79%</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>4 – 6%</td>
<td>2 – 5%</td>
<td>0.39%</td>
<td>0.21%</td>
<td>0.21%</td>
<td>0.2%</td>
<td>1.5/0.15/0.11%</td>
<td>0.10%</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>4 – 6%</td>
<td>2 – 4%</td>
<td>0.49%</td>
<td>0.24%</td>
<td>0.50%</td>
<td>0.3%</td>
<td>0.49/0.33/0.24%</td>
<td>0.05%</td>
</tr>
<tr>
<td>$\kappa_\ell$</td>
<td>6 – 8%</td>
<td>2 – 5%</td>
<td>1.9%</td>
<td>0.98%</td>
<td>1.3%</td>
<td>0.72%</td>
<td>3.5/1.4/&lt;1.3%</td>
<td>0.51%</td>
</tr>
<tr>
<td>$\kappa_d = \kappa_b$</td>
<td>10 – 13%</td>
<td>4 – 7%</td>
<td>0.93%</td>
<td>0.60%</td>
<td>0.51%</td>
<td>0.4%</td>
<td>1.7/0.32/0.19%</td>
<td>0.39%</td>
</tr>
<tr>
<td>$\kappa_u = \kappa_t$</td>
<td>14 – 15%</td>
<td>7 – 10%</td>
<td>2.5%</td>
<td>1.3%</td>
<td>1.3%</td>
<td>0.9%</td>
<td>3.1/1.0/0.7%</td>
<td>0.69%</td>
</tr>
</tbody>
</table>

![Graph 1](#)

![Graph 2](#)
Higgs Self Coupling

Very challenging search / measurements

Cross section at NNLO
arXiv:1309.6594

HL-LHC required to reach SM sensitivity

BSM increase in yields can be substantial

Ebullient discussion of di-Higgs production by theory community

Experimentalists very conservative

References in backup
Channels and Sensitivity

- Promising final states at the LHC
  
  \[ HH \rightarrow b\bar{b}\gamma\gamma \quad \text{and} \quad HH \rightarrow b\bar{b}\tau^{+}\tau^{-} \]

- Difficulties in background estimation
  - esp. fake rate or mistag estimates

- Expected sensitivity
  \[
  \frac{\delta \lambda_{HHH}}{\lambda_{HHH}} = \mathcal{O}(30\%) \]

- Sensitivity enhanced using event shapes

- ATLAS & CMS are developing a program for HL-LHC di-Higgs measurements

- Lepton collider need very large datasets at high energy or extreme precision g_{ZH} measurements

\[
\begin{array}{|c|c|c|c|}
\hline
\sqrt{s} \text{ (GeV)} & \text{HL-LHC} & \text{HE-LHC} & \text{VLHC} \\
\hline
\int Ldt \text{ (fb}^{-1}) & 14000 & 33,000 & 100,000 \\
\hline
\lambda & 50\% & 20\% & 8\% \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\sqrt{s} \text{ (GeV)} & ILC500 & ILC1000 & ILC1000-up & CLIC1400 & CLIC3000 \\
\hline
\int Ldt \text{ (fb}^{-1}) & 500 & 500/1000 & 500/1000 & 1400 & 3000 \\
\hline
\lambda & 83\% & 21\% & 13\% & 21\% & 10\% \\
\hline
\end{array}
\]
Summary
Conclusion

• Higgs physics transitioned from searches to precision measurements

• **Signatures compatible with SM Higgs Boson**
  - Interpretation in numerous BSM model possible
  - Future precision measurements can unveil true nature of this beast

• Exciting experimental and theoretical research program ahead
Resources

- ATLAS public Higgs physics page
- CMS public Higgs physics page
- Tevatron Higgs page
- ATLAS & CMS Snowmass and ECFA reports
- Snowmass Higgs group summary report
Resources on Di-Higgs

1. LHC Physics Review

2. Higgs Trilinear Coupling
   - Florian Goertz, Andreas Papaeftathiou, Li Lin Yang, José Zurita http://arxiv.org/abs/1301.3492

3. Higgs Quartic Coupling

4. BSM interpretation

• incomplete list
Comparison of ATLAS and CMS

<table>
<thead>
<tr>
<th>L(\text{fb}^{-1})</th>
<th>Exp.</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>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>ATLAS</td>
<td>[9, 14]</td>
<td>[8, 13]</td>
<td>[6, 12]</td>
<td>N/a</td>
<td>[16, 22]</td>
<td>[145, 147]</td>
<td>[40, 42]</td>
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<tr>
<td></td>
<td>CMS</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>
</tr>
<tr>
<td>3000</td>
<td>ATLAS</td>
<td>[4, 10]</td>
<td>[5, 9]</td>
<td>[4, 10]</td>
<td>N/a</td>
<td>[12, 19]</td>
<td>[54, 57]</td>
<td>[12, 15]</td>
</tr>
<tr>
<td></td>
<td>CMS</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>[14, 20]</td>
</tr>
</tbody>
</table>

**Uncertainty on signal strength**
- Ranges \([x,y]\) are not directly comparable
- ATLAS
  - [no theory uncertainty, Scenario 1]
- CMS
  - [Scenario 2, Scenario 1]

**Overall reasonable agreement, but**
- ATLAS does not include \(H \rightarrow bb\) mode
- CMS outperforms ATLAS \(H \rightarrow \tau\tau\) mode
- Large differences in \(H \rightarrow Z\gamma\) mode due to photon id
Uncertainty on Signal Strength

Based on parametric simulation

Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: $\Delta$ theory / 2, rest $\propto 1/\sqrt{L}$

Extrapolated from 2011/12 results
LHC Upgrade Stages

**LHC**
Reach $10^{34}$ cm$^{-2}$s$^{-1}$ by LS2, double by LS3 and integrate 300 fb$^{-1}$ by 2022

$<\text{PU}> = 50$

**HL-LHC**
Lumi-level $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$
and integrate 3000 fb$^{-1}$ after L3

$<\text{PU}> = 140$
Higgs Couplings at Lepton Collider

• Higgs-strahlung is main production process
  • HZZ coupling observed at the LHC
  • Vector boson fusion give small contribution at 250 GeV
• Cross section plateau at 240-280 GeV
• Reasonable background level