Higgs Self-Coupling Measurement at the ILC.

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Americas Workshop on Linear Colliders
12-16 May 2014
Introduction

- Higgs properties can be measured precisely at ILC ($m_H$, $\Gamma_H^{\text{tot}}$, etc.)

  missing: **Higgs potential**, which represents test of EWSB and mass generation

- to probe shape of Higgs potential we need to determine the **Higgs self-coupling**
Double Higgs production processes

- **Higgs-strahlung**: dominant around $\sqrt{s} = 500$ GeV

- **WW-fusion**: dominant at high $\sqrt{s}$

Higgs self-coupling at ILC | Americas Workshop on Linear Colliders, 12-16 May 2014 | 2/18
Fundamental difficulties:

- irreducible SM diagrams: significantly degrade the coupling sensitivity
- production cross-sections are small $\rightarrow$ high luminosities needed
- very large SM background
- low-$p_T$ $\gamma\gamma \rightarrow$ hadrons background (analysis with and without overlay)
- BR($H \rightarrow b\bar{b}$) drop to higher Higgs masses
Irreducible diagrams and sensitivity of self-coupling

- irreducible diagrams with same final state, but do not concern self-coupling

- cross-section $\sigma(ZHH)$ as a function of $\lambda$

$$\sigma(\lambda) = a\lambda^2 + b\lambda + c$$

- a: Higgs self-coupling diagram
- b: interference between diagrams
- c: irreducible diagrams

- precision of Higgs self-coupling for $m_H = 125$ GeV

Higgs-strahlung:

$$\frac{\Delta\lambda}{\lambda} = 1.64 \cdot \frac{\Delta\sigma}{\sigma}$$

WW-fusion:

$$\frac{\Delta\lambda}{\lambda} = 0.76 \cdot \frac{\Delta\sigma}{\sigma}$$

w/o interference the factor would be 0.5
Analysis strategy - Decay Channels

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Cross-section [fb]</th>
<th>Expected no. of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+ e^- \rightarrow ZHH$</td>
<td>0.23</td>
<td>460</td>
</tr>
<tr>
<td>$m_H = 120$ GeV</td>
<td></td>
<td></td>
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<tr>
<td>$m_H = 125$ GeV</td>
<td>0.20</td>
<td>396</td>
</tr>
</tbody>
</table>

assuming $P(e^+ e^-) = (0.3, -0.8)$ at $\mathcal{L} = 2$ ab$^{-1}$

$e^+ e^- \rightarrow ZHH \rightarrow l^- l^+ HH$

2leptons 4jets mode ($10\% \times 60\% \times 60\% \approx 3.6\%$)

$Z \rightarrow l\bar{l} \quad H \rightarrow b\bar{b} \quad H \rightarrow b\bar{b}$

$e^+ e^- \rightarrow ZHH \rightarrow \nu\bar{\nu}HH$

2neutrino 4jet mode ($20\% \times 60\% \times 60\% \approx 7.2\%$)

$Z \rightarrow \nu\bar{\nu} \quad H \rightarrow b\bar{b} \quad H \rightarrow b\bar{b}$

$e^+ e^- \rightarrow ZHH \rightarrow q\bar{q}HH$

6jets mode ($70\% \times 60\% \times 60\% \approx 25\%$)

$Z \rightarrow q\bar{q} \quad H \rightarrow b\bar{b} \quad H \rightarrow b\bar{b}$
From $m_H = 120$ GeV to $m_H = 125$ GeV

- smaller cross-section $\sigma_{ZHH}$ to higher Higgs masses

<table>
<thead>
<tr>
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assuming $P(e^+e^-) = (0.3,-0.8)$ at $\mathcal{L} = 2$ ab$^{-1}$

- decreasing branching ratio $BR(H \rightarrow b\bar{b})$
Results for 120 GeV, extrapolation to 125 GeV

- measurement at $\sqrt{s} = 500$ GeV, $\mathcal{L} = 2$ ab$^{-1}$ and $P(e^+e^-) = (0.3, -0.8)$

- results for $m_H = 120$ GeV without $\gamma\gamma$-overlay [Junping Tian, LC-REP-2013-003]

  cross-section: $\frac{\delta \sigma_{ZHH}}{\sigma_{ZHH}} = 27\%$

  Higgs self-coupling: $\frac{\delta \lambda}{\lambda} = 44\%$

- result extrapolated to $m_H = 125$ GeV

<table>
<thead>
<tr>
<th>scenario</th>
<th>$m_H = 120$ GeV</th>
<th>$m_H = 125$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario A: $HH \rightarrow bbbb$</td>
<td>44%</td>
<td>53%</td>
</tr>
<tr>
<td>Scenario B: adding $HH \rightarrow bWW^*$, expect 20% improvement</td>
<td>35%</td>
<td>42%</td>
</tr>
<tr>
<td>Scenario C: analysis improvement (jet-clustering, kinematic fit, etc.), expect 20% improvement</td>
<td>28%</td>
<td>34%</td>
</tr>
</tbody>
</table>

Using ZHH ($H \rightarrow b\bar{b}$) at $\sqrt{s} = 500$ GeV we would expect a precision of 53% on the Higgs self-coupling for $m_H = 125$ GeV
Perform analysis for $m_H = 125 \text{ GeV}$ without and with overlay and investigate the differences

*analysis strategy identical to* LC-REP-2013-003

**NEW** low $p_T \gamma\gamma \rightarrow$ hadrons background

- virtual photons which got radiated off the primary beam electrons
- real photons due to bremsstrahlung and synchrotron radiation

Event selection:

1. isolated lepton selection or rejection
2. $\gamma\gamma$-overlay removal
3. cluster particles into jets and get flavor tag information
4. pair jets to form signal bosons
5. each dominant background is suppressed by training a separate neural net
Strategic difficulties:

- flavor tagging and isolated lepton selection: need very high efficiency and purity
- Higgs mass reconstruction: mis-clustering, wrong jet-pairing
- neural net training: train separate neural nets, large statistics needed
- analysis strategy optimised for ZHH, not just self-coupling diagram
Isolated lepton selection

old lepton selection - isolation requirement: cut based on energy distributions in calorimeter
new lepton selection - isolation requirement: neural net based (MVA)

Example of input variable: energyratio

- define cone around direction of rec. particle and sum up energy of particles inside this cone
- energyratio is $E / (E + E_{cone})$
- isolated lepton has small $E_{cone}$, so energyratio close to one

neural net output for electrons

<table>
<thead>
<tr>
<th>efficiency (%)</th>
<th>eehh</th>
<th>$\mu\mu hh$</th>
<th>bbb</th>
<th>e$\nu$bbqq</th>
<th>$\mu\nu$bbqq</th>
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<tbody>
<tr>
<td>new selection</td>
<td>87.0</td>
<td>89.1</td>
<td>0.0017</td>
<td>0.315</td>
<td>0.020</td>
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<tr>
<td>old selection</td>
<td>85.7</td>
<td>88.4</td>
<td>0.028</td>
<td>1.44</td>
<td>0.10</td>
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</tbody>
</table>

New lepton selection strategy increases signal efficiency.
Suppression of hadronic and one-lepton backgrounds is significantly improved.
Removal of low-$p_T$ $\gamma\gamma \rightarrow$ hadrons background

- low-$p_T$ $\gamma\gamma \rightarrow$ hadrons overlaid events per interaction:
  \[ <N_{\gamma\gamma}> = 1.7 \]
  (ILD/SiD standard, but overestimated)

- apply FastJetClustering: $k_T$ExclusiveNJets
  which R-value?
  \[ \text{for } R \geq 1.2 \text{ almost no increase in signal efficiency but in overlay} \]
  \[ \text{best recovery of bare evts } R = 1.3 \]
  \[ \text{use only reconstructed particles in the clustered jets for analysis} \]
Jet-clustering

- after isolated lepton selection or rejection cluster remaining particles into jets
- clustering algorithm: Durham algorithm

- mis-clustering of particles degrades Higgs mass resolution
- ongoing work: new jet-clustering algorithm
- perfect jet-clustering can improve coupling precision by $\approx 10\%$ or more
Jet-pairing

- combine the jets by choosing combination with smallest $\chi^2$

$$\chi^2 = \frac{(M(j_i,j_j) - M(H))^2}{\sigma_H^2} + \frac{(M(j_k,j_l) - M(H))^2}{\sigma_H^2} + \frac{(M(j_m,j_n) - M(Z))^2}{\sigma_Z^2}$$

- pair 4 jets to H1 and H2

- pair 6 jets to H1, H2 and Z

- Higgs mass resolution important for neural net training (input variables)
- jet-pairing ($\approx 70\%$ correct pairing)
- additionally: investigate kinematic fitting
MarlinKinFit package

E, p conservation
invariant mass constraints

- $M_{ij} = X$ GeV
- $M_{ij} = M_{lk}$
- $M_{ij} = (X \pm Y)$ GeV

ongoing: implementation in Higgs
self-coupling analysis

need: jet-quark comparison,
association via angle differences

best permutation with
smallest sum of angles

$$\sum \alpha_i \text{ btw quark & jet}$$

$$\alpha_i = \frac{\vec{p}_{j1} \cdot \vec{p}_{q1}}{|\vec{p}_{j1}| \cdot |\vec{p}_{q1}|}$$

![Graph showing reconstructed mass vs. entries]

![Graph showing jet mass comparison]

Claude Fabienne Dürig | Higgs self-coupling at ILC | Americas Workshop on Linear Colliders, 12-16 May 2014 | 14/18
Matrix Element Method

ME tools within Marlin framework, thanks to Junping Tian and Keisuke Fujii

\[ \longrightarrow \] talk by Junping Tian ”Matrix Element Method for ILC physics analysis”

**GOAL** implement MEM in Higgs self-coupling analysis

1. **next:** use different MEs for better signal/background separation (ZHH, ZZZ, etc.)

2. **future:** optimise selection for self-coupling diagram in ZHH: ME irreducible diagrams, ME self-coupling diagram
Preliminary results for 125 GeV without overlay

- $m_H = 120$ GeV results extrapolated to 125 GeV give precision of 53% on Higgs self-coupling
- preliminary results without overlay

<table>
<thead>
<tr>
<th>modes</th>
<th>signal</th>
<th>background</th>
<th>significance excess</th>
<th>significance measurement</th>
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<tbody>
<tr>
<td>$ZHH \rightarrow l^- l^+ HH$</td>
<td>3.0</td>
<td>4.3</td>
<td>1.16$\sigma$</td>
<td>0.91$\sigma$</td>
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<tr>
<td></td>
<td>3.3</td>
<td>6.0</td>
<td>1.12$\sigma$</td>
<td>0.91$\sigma$</td>
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<td>$ZHH \rightarrow \nu \bar{\nu} HH$</td>
<td>5.4</td>
<td>7.0</td>
<td>1.72$\sigma$</td>
<td>1.45$\sigma$</td>
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<tr>
<td>$ZHH \rightarrow q\bar{q} HH$</td>
<td>9.1</td>
<td>21.3</td>
<td>1.78$\sigma$</td>
<td>1.61$\sigma$</td>
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<tr>
<td></td>
<td>9.0</td>
<td>34.7</td>
<td>1.41$\sigma$</td>
<td>1.30$\sigma$</td>
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Cross-section: $\frac{\delta \sigma_{ZHH}}{\sigma_{ZHH}} = 32\%$

Higgs self-coupling: $\frac{\delta \lambda}{\lambda} = 52\%$

Scenario A: $HH \rightarrow bbb\bar{b}$
Scenario B: adding $HH \rightarrow bbWW^*$, expect 20% improvement
Scenario C: analysis improvement (kinematic fit, jet-clustering, etc.) expect 20% improvement

We achieve a precision of 52% on the Higgs self-coupling for $m_H = 125$ GeV!

Effect of $\gamma\gamma$-overlay?
Preliminary results for 125 GeV with overlay

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<tr>
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<th>background</th>
<th>significance</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>excess</td>
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<tr>
<td>(ZHH \rightarrow l^- l^+ HH)</td>
<td>2.4</td>
<td>4.0</td>
<td>0.94(\sigma)</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
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<td>1.01(\sigma)</td>
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<tr>
<td>(ZHH \rightarrow \nu \bar{\nu} HH)</td>
<td>3.8</td>
<td>4.0</td>
<td>1.53(\sigma)</td>
</tr>
<tr>
<td>(ZHH \rightarrow qqHH)</td>
<td>8.3</td>
<td>22.3</td>
<td>1.59(\sigma)</td>
</tr>
<tr>
<td></td>
<td>8.7</td>
<td>39.3</td>
<td>1.29(\sigma)</td>
</tr>
</tbody>
</table>

Cross-section: \(\frac{\delta \sigma_{ZHH}}{\sigma_{ZHH}} = 36.2\%\)

Higgs self-coupling: \(\frac{\delta \lambda}{\lambda} = 59.4\%\)

Scenario A: \(HH \rightarrow bbbb\)

Scenario B: with \(HH \rightarrow bbWW^*\), \(\approx 20\%\) improvement

Scenario C: analysis improvement (kinematic fit, jet-clustering, etc.) expect \(20\%\) improvement

Considering \(\gamma\gamma\)-overlay, we achieve a precision of \(59\%\) on the Higgs self-coupling

After 10 years of running ILC we can achieve a precision of 10\% on the Higgs self-coupling (w/o overlay)

Summary and Outlook

Ongoing work

- key algorithms: b-tagging, lepton selection, jet-finding, jet-clustering
- investigate kinematic fitting (Benjamin Hermberg, DESY)
- Matrix Element Method (Junping Tian & Keisuke Fujii, KEK)
- optimise analysis strategy (now optimised for ZHH, not for self-coupling diagram)
- analysis with H→WW* (Masakazu Kurata, University of Tokyo) → next talk

Conclusion

- measuring Higgs self-coupling is fundamental task for next generation LC
- direct determination of Higgs potential through double Higgs production
- measurement of Higgs self-coupling challenging
- considering γγ—overlay
- preliminary results for m_H = 125 GeV gives precision of 59.4% at √s = 500 GeV
- starting points for improvement
- long term perspective: at 1 TeV achieve precision of < 10%
Analysis strategy

\[ l^- l^+ HH \]
- select two isolated charged leptons consistent with \( M_Z \)
- cluster other particles into four jets
- pair four jets to form two Higgs bosons
- neural net analysis performed

\[ \nu\nu HH \]
- reject events with isolated charged leptons
- cluster other particles into four jets
- pair four jets to form two Higgs bosons
- use flavor tagging information
- neural net analysis performed

\[ qq HH \]
- reject events with isolated charged leptons
- cluster other particles into six jets
- pair six jets to form two Higgs bosons and a Z-boson
- use flavor tagging information
- neural net analysis performed
### Leptonic Channel: Optimised Cuts

#### Electron Type

**Optimised with Overlay**
- **Cut 1**: \(|M_Z - 91 \text{ GeV}| < 32 \text{ GeV}
- **Cut 2**: MVAllbb > 0.79
- **Cut 3**: MVAlvbbqq > 0.81
- **Cut 4**: bmax3 > 0.22
- **Cut 5**: MVAllbbbb > 0.3

**Optimised without Overlay**
- **Cut 1**: \(|M_Z - 91 \text{ GeV}| < 32 \text{ GeV}
- **Cut 2**: MVAllbb > 0.78
- **Cut 3**: MVAlvbbqq > 0.62
- **Cut 4**: bmax3 > 0.18
- **Cut 5**: MVAllbbbb > 0.25

#### Muon Type

**Optimised with Overlay**
- **Cut 1**: \(|M_Z - 91 \text{ GeV}| < 32 \text{ GeV}
- **Cut 2**: MVAllbb > 0.71
- **Cut 3**: MVAlvbbqq > 0.65
- **Cut 4**: bmax3 > 0.13
- **Cut 5**: MVAllbbbb > 0.27

**Optimised without Overlay**
- **Cut 1**: \(|M_Z - 91 \text{ GeV}| < 32 \text{ GeV}
- **Cut 2**: MVAllbb > 0.78
- **Cut 3**: MVAlvbbqq > 0.84
- **Cut 4**: bmax3 > 0.13
- **Cut 5**: MVAllbbbb > 0.24
### leptonic channel: cutflow - electron type

#### without overlay

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<th>ltype = 11</th>
<th>ee bb</th>
<th>mu bb</th>
<th>eν bb qq</th>
<th>μν bb qq</th>
<th>τ ν bb qq</th>
<th>bb qq qq</th>
<th>bb bb</th>
<th>lllb bb</th>
<th>lllq H</th>
<th>bgrd</th>
<th>signal (ll4b)</th>
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<td>284117</td>
<td>49565.7</td>
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<td>2660.9</td>
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### Leptonic Channel: Cutflow - Muon Type

#### Without Overlay

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<th></th>
<th>eebb</th>
<th>μμbb</th>
<th>eνbbqq</th>
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optimised with overlay

- **cut1:**
  \[ E_{vis} < 372 \text{ GeV} + 0.83 \cdot P_{miss}^t, \]
  \[ M_Z < 60 \text{ GeV} \]

- **cut2:**
  \[ \text{npfos}_{min} > 10, \]
  \[ M(HH) < 200 \text{ GeV}, \]
  \[ 103 \text{ GeV} < M(H1) < 141 \text{ GeV}, \]
  \[ 103 \text{ GeV} < M(H1) < 136 \text{ GeV} \]

- **cut3:**
  \[ \text{MVAbbbb} > 0.93 \]

- **cut4:**
  \[ \text{MVALvqqqq} > 0.73 \]

- **cut5:**
  \[ \text{MVAvvbbbb} > 0.3 \]

- **cut6:**
  \[ b_{max3} + b_{max4} > 1.1 \]

optimised without overlay

- **cut1:**
  \[ E_{vis} < 364 \text{ GeV} + 0.83 \cdot P_{miss}^t, \]
  \[ M_Z < 60 \text{ GeV} \]

- **cut2:**
  \[ \text{npfos}_{min} > 6, \]
  \[ M(HH) < 200 \text{ GeV}, \]
  \[ 100 \text{ GeV} < M(H1) < 139 \text{ GeV}, \]
  \[ 91 \text{ GeV} < M(H1) < 134 \text{ GeV} \]

- **cut3:**
  \[ \text{MVAbbbb} > 0.93 \]

- **cut4:**
  \[ \text{MVALvqqqq} > 0.66 \]

- **cut5:**
  \[ \text{MVAvvbbbb} > 0.56 \]

- **cut6:**
  \[ b_{max3} + b_{max4} > 1.08 \]
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hadronic channel: opt. cuts - dominant bbHH

optimised with overlay

- **cut1**: \( \text{prop31} + \text{prob32} > 0.54 \)
- **cut2**:
  \[
P_t^{\text{miss}} < 77 \text{ GeV}, \quad npfos > 245, \quad 37 \text{ GeV} < M(Z) < 136 \text{ GeV}, \quad 83 \text{ GeV} < M(H1) < 159 \text{ GeV}, \quad 62 \text{ GeV} < M(H1) < 162 \text{ GeV}
  \]
- **cut3**: \( \text{MVAbbbb} > 0.83 \)
- **cut4**: \( \text{MVAbbqqqq} > 0.51 \)
- **cut5**: \( \text{MVAqbbbbb} > 0.16 \)
- **cut6**: \( b_{\text{max}}3 + b_{\text{max}}4 > 1.21 \)

optimised without overlay

- **cut1**: \( \text{prop31} + \text{prob32} > 0.54 \)
- **cut2**:
  \[
P_t^{\text{miss}} < 80 \text{ GeV}, \quad npfos > 246, \quad 34 \text{ GeV} < M(Z) < 136 \text{ GeV}, \quad 81 \text{ GeV} < M(H1) < 170 \text{ GeV}, \quad 73 \text{ GeV} < M(H1) < 167 \text{ GeV}
  \]
- **cut3**: \( \text{MVAbbbb} > 0.71 \)
- **cut4**: \( \text{MVAbbqqqq} > 0.48 \)
- **cut5**: \( \text{MVAqbbbbb} > 0.14 \)
- **cut6**: \( b_{\text{max}}3 + b_{\text{max}}4 > 1.22 \)
hadronic channel: cutflow - dominant bbHH

without overlay
with overlay

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hadronic channel: opt. cuts - dominant light qqHH

optimised with overlay

- **cut1:** $\text{prop31} + \text{prob32} < 0.54$
- **cut2:**
  - $P_t^{\text{miss}} < 77 \text{ GeV}$,
  - $\text{npfos} > 245$,
  - $65 \text{ GeV} < M(\text{Z}) < 133 \text{ GeV}$,
  - $100 \text{ GeV} < M(\text{H1}) < 136 \text{ GeV}$,
  - $96 \text{ GeV} < M(\text{H1}) < 141 \text{ GeV}$
- **cut3:** $\text{MVAbbbb} > 0.73$
- **cut4:** $\text{MVAbbqqqq} > 0.52$
- **cut5:** $\text{MVAqqbbbbb} > 0.11$
- **cut6:**
  - $b_{\text{max}3} > 0.92$,
  - $b_{\text{max}3} + b_{\text{max}4} > 1.37$

optimised without overlay

- **cut1:** $\text{prop31} + \text{prob32} < 0.54$
- **cut2:**
  - $P_t^{\text{miss}} < 80 \text{ GeV}$,
  - $\text{npfos} > 246$,
  - $64 \text{ GeV} < M(\text{Z}) < 129 \text{ GeV}$,
  - $104 \text{ GeV} < M(\text{H1}) < 134 \text{ GeV}$,
  - $98 \text{ GeV} < M(\text{H1}) < 140 \text{ GeV}$
- **cut3:** $\text{MVAbbbb} > 0.59$
- **cut4:** $\text{MVAbbqqqq} > 0.43$
- **cut5:** $\text{MVAqqbbbbb} > 0.15$
- **cut6:**
  - $b_{\text{max}3} > 0.91$,
  - $b_{\text{max}3} + b_{\text{max}4} > 1.38$
hadronic channel: cutflow - dominant light qqHH

without overlay
with overlay

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<td>196.2</td>
<td>338.7</td>
<td>141.1</td>
<td>1263.7</td>
<td>2132.6</td>
<td>6.8</td>
<td>17.2</td>
<td>27.2</td>
<td>49.6</td>
<td>4173.1</td>
<td>21.9 (18.4)</td>
</tr>
<tr>
<td>cut3 (mlp1)</td>
<td>12.3</td>
<td>81.8</td>
<td>62.4</td>
<td>741.1</td>
<td>1431.1</td>
<td>4.6</td>
<td>12.4</td>
<td>21.5</td>
<td>40.1</td>
<td>2407.3</td>
<td>19.5 (16.8)</td>
</tr>
<tr>
<td></td>
<td>13.9</td>
<td>134.0</td>
<td>128.8</td>
<td>1116.5</td>
<td>1866.8</td>
<td>5.6</td>
<td>15.1</td>
<td>26.5</td>
<td>47.4</td>
<td>3354.6</td>
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<tr>
<td>cut4 (mlp2)</td>
<td>11.8</td>
<td>65.5</td>
<td>51.6</td>
<td>549.8</td>
<td>989.3</td>
<td>4.5</td>
<td>12.2</td>
<td>21.1</td>
<td>38.9</td>
<td>1744.8</td>
<td>19.2 (16.6)</td>
</tr>
<tr>
<td></td>
<td>11.9</td>
<td>109.6</td>
<td>82.1</td>
<td>666.7</td>
<td>1034.3</td>
<td>5.1</td>
<td>14.1</td>
<td>25.2</td>
<td>42.7</td>
<td>1991.9</td>
<td>19.0 (16.1)</td>
</tr>
<tr>
<td>cut5 (mlp3)</td>
<td>11.3</td>
<td>64.7</td>
<td>50.3</td>
<td>541.7</td>
<td>973.4</td>
<td>4.1</td>
<td>12.1</td>
<td>21.1</td>
<td>38.7</td>
<td>1717.4</td>
<td>19.1 (16.5)</td>
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<tr>
<td></td>
<td>11.8</td>
<td>109.6</td>
<td>81.2</td>
<td>661.7</td>
<td>1028.9</td>
<td>4.9</td>
<td>14.0</td>
<td>25.2</td>
<td>42.6</td>
<td>1979.9</td>
<td>18.9 (16.0)</td>
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<tr>
<td>cut6 (bmax3)</td>
<td>4.6</td>
<td>0.3</td>
<td>2.9</td>
<td>5.2</td>
<td>4.9</td>
<td>1.7</td>
<td>4.6</td>
<td>4.3</td>
<td>6.0</td>
<td>34.7</td>
<td>9.0 (8.2)</td>
</tr>
<tr>
<td></td>
<td>5.6</td>
<td>0.5</td>
<td>2.4</td>
<td>6.2</td>
<td>5.1</td>
<td>2.0</td>
<td>5.8</td>
<td>5.0</td>
<td>6.6</td>
<td>39.3</td>
<td>8.7 (7.9)</td>
</tr>
</tbody>
</table>
Preliminary results for \(m_H = 125\) GeV with overlay

preliminary results for \(m_H = 125\) GeV without overlay:

<table>
<thead>
<tr>
<th>modes</th>
<th>signal</th>
<th>background</th>
<th>significance</th>
<th>excess</th>
<th>measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>(ZHH \to l^- l^+ HH)</td>
<td>3.0</td>
<td>4.3</td>
<td>1.16σ</td>
<td>0.91σ</td>
<td></td>
</tr>
<tr>
<td>(ZHH \to \nu \bar{\nu} HH)</td>
<td>5.4</td>
<td>7.0</td>
<td>1.72σ</td>
<td>1.45σ</td>
<td></td>
</tr>
<tr>
<td>(ZHH \to q\bar{q} HH)</td>
<td>9.1</td>
<td>21.3</td>
<td>1.78σ</td>
<td>1.61σ</td>
<td></td>
</tr>
</tbody>
</table>

We achieve a combined signal significance of \(s\sigma = 3.8\sigma\)

We achieve a precision on the Higgs self-coupling without weighting of 56.7%

preliminary results for \(m_H = 125\) GeV with overlay:

<table>
<thead>
<tr>
<th>modes</th>
<th>signal</th>
<th>background</th>
<th>significance</th>
<th>excess</th>
<th>measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>(ZHH \to l^- l^+ HH)</td>
<td>2.4</td>
<td>4.0</td>
<td>0.94σ</td>
<td>0.72σ</td>
<td></td>
</tr>
<tr>
<td>(ZHH \to \nu \bar{\nu} HH)</td>
<td>3.2</td>
<td>7.0</td>
<td>1.01σ</td>
<td>0.83σ</td>
<td></td>
</tr>
<tr>
<td>(ZHH \to q\bar{q} HH)</td>
<td>3.8</td>
<td>4.0</td>
<td>1.53σ</td>
<td>1.22σ</td>
<td></td>
</tr>
</tbody>
</table>

Considering overlay, we achieve a combined signal significance of \(s\sigma = 2.9\sigma\)

We achieve a precision on the Higgs self-coupling without weighting of 63%
Cross-section and self-coupling determination

- Cross-section measurement via parameter estimation through **minimum likelihood method**
- Define likelihood:

\[
L_{s+b} = \prod_i e^{-(s_i + b_i)} \frac{(s_i + b_i)^{n_i}}{n_i!}
\]

\[
L_b = \prod_i \frac{1}{n_i!} e^{-b_i b_i^{n_i}}
\]

- Only \( s_i \) (i = search mode) is related to \( \sigma_{ZHH} \):

\[
s_i = \sigma_{ZHH} \cdot L \cdot BR_i \cdot \epsilon_i
\]

- Minimisation of

\[
\chi^2 = -2 \ln \left( \frac{L_b}{L_{s+b}} \right)
\]

gives minimum \( \sigma_{ZHH} \cdot L \)

- Precision of Higgs self-coupling:

\[
\frac{\Delta \lambda}{\lambda} = 1.64 \cdot \frac{\Delta \sigma}{\sigma}
\]

for \( m_H = 125 \text{ GeV} \) at \( \sqrt{s} = 500 \text{ GeV} \)
Excess and measurement significance

**Excess significance**: assuming there is no signal, the probability of observing events equal or more than the expected number of events ($N_S + N_B$)

$$p = \int_{N_S + N_B}^{\infty} f(x; N_B)dx$$

in case of large statistics: $$\frac{N_S}{\sqrt{N_B}}$$

**Measurement significance**: assuming signal exists, the probability of observing events equal or less than the expected number of background events ($N_B$)

$$p = \int_{-\infty}^{N_B} f(x; N_S + N_B)dx$$

in case of large statistics: $$\frac{N_S}{\sqrt{N_S + N_B}}$$

Convert to gaussian significance ($s$):

$$1 - p = \int_{-\infty}^{s\sigma} N(x; 0, 1)dx$$
process used: $HH \rightarrow bb\gamma\gamma$

investigated energies: $\sqrt{s} = 14$ TeV, $\sqrt{s} = 33$ TeV, $\sqrt{s} = 100$ TeV

integrated luminosity: $\mathcal{L} = 3$ ab$^{-1}$

<table>
<thead>
<tr>
<th>energy precision</th>
<th>$\sqrt{s} = 14$ TeV</th>
<th>$\sqrt{s} = 33$ TeV</th>
<th>$\sqrt{s} = 100$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>precision</td>
<td>50%</td>
<td>20%</td>
<td>8%</td>
</tr>
</tbody>
</table>

high luminosity running at $\sqrt{s} = 14$ TeV, possible to observe signal with statistical significance of $2.3\sigma$ with $\mathcal{L} = 3$ ab$^{-1}$ of data

at $\sqrt{s} = 33$ TeV, expect to observe signal with statistical significance of $6.2\sigma$ with $\mathcal{L} = 3$ ab$^{-1}$

at $\sqrt{s} = 100$ TeV, expect to observe signal with statistical significance of $15.0\sigma$ with $\mathcal{L} = 3$ ab$^{-1}$
Durham clustering algorithm

- Durham algorithm clusters the 2 objects i and j with the smallest mutual angle $\theta_{ij}$ and energy $\min(E^2_i, E^2_j)$.

- **Algorithm work iterative**: beginning with a list of jets that are all just particles.

- between every particle pair (i,j) the relative distance $y_{ij}$ is determined from
  - the energies $E_i, E_j$ of the particles
  - and their mutual angle $\theta_{ij}$

  by:

  $$y_{ij} = \frac{2\min(E^2_i, E^2_j)(1 - \cos\theta_{ij})}{E_{vis}^2}$$

- two particles with smallest relative distance value $y_{ij}$ are combined to a new object with four-momentum:

  $$p^\mu_k = p^\mu_i + p^\mu_j$$

In figure object 3 and 4 are clustered to a new object 3∗.
Color-singlet Jet-clustering (challenging)

scatter plot of two Higgs masses

- the mis-clustering of particles degrades the mass resolution very much
- it is studied using perfect color-singlet jet-clustering can improve $\delta \lambda \sim 40\%$
- Mini-jet based clustering (Durham works when Np in mini-jet $\sim 5$, need better algorithm to combine the mini-jets, using such as color-singlet dynamics: rapidity gap, coplanarity, energy pdf)