The Higgs Potential at future colliders

Michele Selvaggi (CERN)
Self coupling @ HL-LHC measurements

At the (HL-)LHC the self-coupling can be measured via both:

- Higgs pair production
- single Higgs production

Indirect constraint from ggH and ttH:

- $\delta\kappa_\lambda \approx 100\%$ (exclusive)
- $\delta\kappa_\lambda \approx 200\%$ (global)

Direct measurement:

- $\delta\kappa_\lambda \approx 50\%$

Indirect constraint from ggH and ttH: $\delta\kappa_\lambda \approx 100\%$ (exclusive) $\delta\kappa_\lambda \approx 200\%$ (global)

Direct measurement: $\delta\kappa_\lambda \approx 50\%$
Self-coupling at circular e⁺e⁻ colliders

- At low energy $\sqrt{s} < 500$ GeV the self-coupling is measured via single Higgs production (FCC-ee)
- Precise ZH cross-section measurement at various energies can resolve $\lambda_3, \lambda_{VVHH}$
- FCC-ee gives the best indirect measurement:
  - $\delta \kappa_\lambda = 33\%$ (2 IPs)
  - $\delta \kappa_\lambda = 24\%$ (4 IPs)

<table>
<thead>
<tr>
<th>Collider</th>
<th>HL-LHC</th>
<th>ILC₂₅₀</th>
<th>CLIC₃₈₀</th>
<th>CEPC₂₄₀</th>
<th>FCC-ee₂₄₀→₃₆₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi (ab⁻¹)</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>5.6</td>
<td>5 + 0.2 + 1.5</td>
</tr>
<tr>
<td>Years</td>
<td>10</td>
<td>11.5</td>
<td>8</td>
<td>7</td>
<td>3 + 1 + 4</td>
</tr>
<tr>
<td>$g_{HHH}$ (%)</td>
<td>50.</td>
<td>- / 49.</td>
<td>- / 50.</td>
<td>- / 50.</td>
<td>44., 33. 2IP</td>
</tr>
</tbody>
</table>

$g_{HHH}$ (27., 24. 4IP)

global fit, with/without HL-LHC input
Self-coupling at linear $e^+e^-$ colliders

- At high energies $\sqrt{s} > 500$ GeV self-coupling is measured via double Higgs production ($ZHH$ and $\nu\nuHH$).
- Cross-section at various energies depends on $\lambda_3$.
- Measured in $l\bar{l}bb\bar{b}$ ($ZHH$) and $\nu\nu\nu\nu\bar{b}\bar{b}W\bar{W}$ ($\nu\nuHH$).

**ILC - 1 TeV**

- $\delta k_3 = 10\%$ (ILC$_{1000}$)
- $\delta k_3 = 9\%$ (CLIC$_{3000}$)

**CLIC - 3 TeV**

<table>
<thead>
<tr>
<th>Collider</th>
<th>ILC$_{500}$</th>
<th>ILC$_{1000}$</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{HHH}$ (%)</td>
<td>27.</td>
<td>10.</td>
<td>9.</td>
</tr>
</tbody>
</table>

1910.00012 [hep-ph]

1901.05897 [hep-ex]
Self-coupling at the FCC-hh

- At 100 TeV pp, Higgs pair production gives best precision on $\lambda_3$
- Measured in:
  - $bb\gamma\gamma$ (golden channel), $bb\tau\tau$, $bbbb$, $bbZZ(4l)$
- Combined precision:
  - 3.5–7% for SM (3% stat. only)
  - 10–20% for $\lambda_3 = 1.5 \times \lambda_3^{\text{SM}}$
Self-coupling at the Muon Collider

Buttazzo, Franceschini, Wulzer

• At 10-30 TeV muon collider, the VBF pair production dominates (~ CLIC)

• \( vvbbbb \) final state (4jets + ME)

• Muon collider could potentially provide the best precision \(~2\%\) (stat only)?

• More studies needed, parton level only for now
Open questions:

- For simplicity, most of the **benchmarking on future colliders capabilities** in made assuming $\lambda_3^{SM}$ (allows for easy comparison), or varying $\lambda_3$ alone.
  
  - desirable to investigate use of global — (SM)EFT fit from exp. community, or this exercise can be left to theorists?
  - how about indirect measurements? (e.g. single Higgs production or W/Z mass)
  - how approach global fits as a community (pheno/exp)

- Various proposed future colliders present different **levels of maturity**
  - How do we deal with detector effects (Pile-up, Beam Induced Background) ?
    - Can be indirectly **parameterised** if full-sim is not available (very different environment) ?
  - Treatment of dominant systematic uncertainties (theory vs. exp)
  - How do we estimate **uncertainties** (performance/systematics) on future colliders?
Open questions:

- What is the **interplay between auxiliary measurements** at various colliders to allow for best self-coupling precision? e.g.
  - at proton collider precise measurement of $\lambda_3$ requires $y_t$ (itself requiring $g_{ttZ}$)?
  - at lepton (and proton) colliders need both measurements of $\lambda_{VVHH}$ and $\lambda_3$

- How about $\lambda_{VVHH}$ and $\lambda_4$?
  - missing exp. efforts so far (see backup for pheno. work)
Open questions

• A strongly first-order EWPT requires new physics coupling to the Higgs.

• What does this imply generically for di-Higgs rates?

• Does it imply a minimum deviation pattern in Higgs couplings?

• How does the reach of Higgs coupling measurements compare to other direct and indirect probes?

• What can we learn about the history of the universe from collider measurements?
BACKUP
The Standard Model Higgs Potential

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

\[ \rightarrow -\frac{\lambda}{4} v^4 + \frac{1}{2} (2\lambda v^2) h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4 \]

\[ = V_0 + \frac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4 \]

- Fix the two parameters \((\mu^2, \lambda)\) with two observables \((v, m_h)\).
- Predictions:

\[ \lambda_3 = \lambda_4 = \frac{m_h^2}{2v^2} \]
Testing the SM Higgs Potential

- Measure di-Higgs (tri-Higgs?) production to probe $\lambda_3$ ($\lambda_4$):

- Must be part of a global fit to Higgs couplings, requires high SM precision!

[talk by M. Selvaggi]

de Blas et al. 1905.03764

talk by M. Selvaggi
e.g. Di Vita, Grojean, Riembau, Vantalon 1704.01953

de Blas et al. 1905.03764
Testing the SM Higgs Potential

- Look for NLO effects of $\lambda_3$ in single Higgs production:

[McCullough 1312.3322; Maltoni, Pagani, Shivaji, Zhao 1709.08649]
Testing the SM Higgs Potential

• Look for effects of $\lambda_3$ in precision electroweak observables:

[Degrassi, Fedele, Giardino 1702.01737; Kribs, Maier, Rzehak, Spannowsky, Waite 1702.07678]
Higgs Potential Beyond the SM

• Heavy new physics can yield effective operators that modify the potential.

  [e.g. Giudice, Grojean, Pomarol, Rattazzi hep-ph/0703164; Brivio, Trott 1706.08945]

\[
\mathcal{L} \supset \frac{c_H}{2\Lambda^2} [\partial_\mu (H^\dagger H)]^2 - \frac{c_6 \lambda}{\Lambda^2} (H^\dagger H)^3
\]

\[
\frac{\lambda_3}{\lambda_3^{SM}} = 1 + c_6 \frac{v^2}{\Lambda^2} - \frac{3}{2} \frac{c_H v^2}{\Lambda^2}
\]

\[
\frac{\lambda_4}{\lambda_4^{SM}} = 1 + \left( 6c_6 - \frac{25}{3} c_H \right) \frac{v^2}{\Lambda^2}
\]

• Note: $c_H$ also modifies $hhVV$ couplings!
Higgs Potential Beyond the SM

- Higgs mixing with other fields or new sources of EWSB can too.

\[ e.g. \]

<table>
<thead>
<tr>
<th>Model</th>
<th>( \max\left{ \frac{\lambda_3}{\lambda_3^{SM}} - 1 \right} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed-in Singlet</td>
<td>(-18%)</td>
</tr>
<tr>
<td>Composite Higgs</td>
<td>(O(10%))</td>
</tr>
<tr>
<td>MSSM</td>
<td>(-15%)</td>
</tr>
<tr>
<td>NMSSM</td>
<td>(-25%)</td>
</tr>
</tbody>
</table>

[Gupta, Rzehak, Wells 1305.6397]
Higgs Potential in the Early Universe

- Thermal effective potential:

\[ V(\phi, T) \sim (\xi T^2 - \mu^2)\phi^2 - AT(\phi^2 + B)^{3/2} + \lambda\phi^4 \]

→ electroweak phase transition (EWPT)
Electroweak Phase Transition

- SM: the electroweak phase transition is a smooth crossover.  \[\text{[Kajantie et al. hep-lat/9510020]}\]

- BSM: the EWPT can be strongly first order if new physics couples to the Higgs.

- A strong first-order EWPT can allow baryogenesis or make gravitational waves!
  \[\text{[e.g. Shaposhnikov NPB287, 575; Kamionkowski, Kosowsky, Turner astro-ph/9310044;}
A First Order EWPT

- Requires new physics that couples to the Higgs.
- SM-charged new physics ⇒ modified Higgs production and decay rates.
  e.g. gluon fusion rates rule out a SFO EWPT from light stops in the MSSM
  [Cohen, DM, Pierce 1203.2924; Curtin, Jaiswal, Meade 1203.2932]
- SM-singlet new physics - main effect can be to alter the self-coupling $\lambda_3$.
  - Higgs-singlet portal: $\lambda_{HS} S^2 H^\dagger H$
  - SMEFT operator: $\frac{c_6}{\Lambda^2} (H^\dagger H)^3$

  [Noble, Perelstein 0711.3018; Profumo, Ramsey-Musolf, Wainwright, Winslow 1407.5342; Curtin, Meade, Yu 1409.0005]
  [Grojean, Servant, Wells hep-ph/0407019; Noble, Perelstein 0711.3018]
A First Order EWPT with Singlet

- For the Higgs-singlet portal: \( \lambda_{HS} S^2 H^\dagger H \)

[CURTIN, MEADE, YU 1409.0005; KOTWAL, RAMSEY-MUSOLF, NO, WINSLOW 1605.06123; HUANG, LONG, WANG 1608.06619; BENIWAL, LEWICKI, WELLS, WHITE, WILLIAMS 1702.06124]
The Standard Model Higgs Potential

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

- hierarchy problem
- Higgs metastability

[KC Green, gunshowcomic.com]
(Higgs) Potential Questions

• What can we learn about new physics from Higgs couplings?

• A strongly first-order EWPT requires new physics coupling to the Higgs:
  
  • What does this imply generically for di-Higgs rates?

  • Does it imply a minimum deviation pattern in Higgs couplings?

  • How does the reach of Higgs coupling measurements compare to other direct and indirect probes?
Higgs Potential Beyond the SM

• **Note 1**: extractions of $\lambda_3$ are sensitive to other deviations in Higgs couplings as well as uncertainties in SM parameters.

• **Note 2**: some BSM scenarios can even interfere with the full realization of electroweak symmetry at high temperature.  
  [e.g. Meade, Ramani 1807.07578; Baldes, Servant 1807.08770]

• **Note 3**: in Higgs-singlet scenarios with a first-order EWPT, finding the new (mostly) singlet scalar might be easier than measuring Higgs rates.

\[
pp \rightarrow h_2^{(\ast)} \rightarrow hh
\]

[Kotwal, Ramsey-Musolf, No, Winslow 1605.06123; Papaefstathiou, White 2010.00597]
Summary future $\lambda_3$ measurements

1) LHC
   - $O(10)$-$O(2)$
   - Could detect large anomalous coupling

2) HL-LHC
   - $O(1)$
   - Potential for evidence (3\(\sigma\) precision)

3) CEPC/FCC-ee: single H couplings + indirect measurement
   - Potential for observation (5\(\sigma\) precision)
   - $\delta g_{ttZ} \sim 1\%$, allows for $\delta y_t \sim 1\%$ @FCC-hh

4) ILC/CLIC: $\sim 10$ % precision

5) FCC-hh: precision measurement: 3.5-7.8%

6) Muon Collider: precision 2-3% (stat only) ?

Global fit in indirect ee measurements

<table>
<thead>
<tr>
<th>collider</th>
<th>1-parameter</th>
<th>full SMEFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEPC 240</td>
<td>18%</td>
<td>-</td>
</tr>
<tr>
<td>FCC-ee 240</td>
<td>21%</td>
<td>-</td>
</tr>
<tr>
<td>FCC-ee 240/365</td>
<td>21%</td>
<td>44%</td>
</tr>
<tr>
<td>FCC-ee (4IP)</td>
<td>15%</td>
<td>27%</td>
</tr>
<tr>
<td>ILC 250</td>
<td>36%</td>
<td>-</td>
</tr>
<tr>
<td>ILC 250/500</td>
<td>32%</td>
<td>58%</td>
</tr>
<tr>
<td>ILC 250/500/1000</td>
<td>29%</td>
<td>52%</td>
</tr>
<tr>
<td>CLIC 380</td>
<td>117%</td>
<td>-</td>
</tr>
<tr>
<td>CLIC 380/1500</td>
<td>72%</td>
<td>-</td>
</tr>
<tr>
<td>CLIC 380/1500/3000</td>
<td>49%</td>
<td>-</td>
</tr>
</tbody>
</table>

[hep-ph]
Higgs Self-coupling and constraints on models with 1st order EWPT

- **Strong 1st order EWPT** needed to explain large observed baryon asymmetry in our universe
- Can be achieved with extension of SM + singlet

Direct detection of extra Higgs states

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh

Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.
$V_L V_L \rightarrow HH$

$A(V_L V_L \rightarrow HH) \sim \frac{\delta}{v^2} (c_{2V} - c_V^2) + \mathcal{O}(m_W^2/\hat{s})$. 

high energy behaviour driven by $C_{2V}$ and $C_V$, if $\delta C_{2V} \neq 0$, grows with $E$

With $c_V$ from FCC-ee, $\delta c_{2V} < 1\%$
$HHH \rightarrow bbbbbbb$

$\chi^2 = \sum_{qr \in \text{pairings}} (M_{qr} - m_h^2)^2$

$SM \text{ significance } \sim 1.7\sigma$

$d_4 \in [-1.7, 13.3]$

<table>
<thead>
<tr>
<th>$hhh \rightarrow \text{final state}$</th>
<th>BR (%)</th>
<th>$N_{20ab^{-1}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(bb)(bb)(bb)$</td>
<td>19.21</td>
<td>22207</td>
</tr>
<tr>
<td>$(bb)(bb)(WW_{1\ell})$</td>
<td>7.20</td>
<td>8328</td>
</tr>
<tr>
<td>$(bb)(bb)(\tau\tau)$</td>
<td>6.31</td>
<td>7297</td>
</tr>
<tr>
<td>$(bb)(bb)(WW_{2\ell})$</td>
<td>1.58</td>
<td>1824</td>
</tr>
<tr>
<td>$(bb)(WW_{1\ell})(WW_{1\ell})$</td>
<td>0.98</td>
<td>1128</td>
</tr>
<tr>
<td>$(bb)(WW_{1\ell})(WW_{2\ell})$</td>
<td>0.90</td>
<td>1041</td>
</tr>
<tr>
<td>$(bb)(\tau\tau)(\tau\tau)$</td>
<td>0.69</td>
<td>799</td>
</tr>
<tr>
<td>$(bb)(bb)(\gamma\gamma)$</td>
<td>0.23</td>
<td>263</td>
</tr>
</tbody>
</table>

[AAR: Tetsutani, Xolooz, Zono, 1909.09106]

[1909.09166 [hep-ph]]
Quartic bounds from di-Higgs

\[ \kappa_4 \in [-2.3, 4.3] \text{ at } 68\% \text{CL} \]