Path towards measuring the Higgs potential

Elisabeth Petit (CPPM, AMU/CNRS/IN2P3)
on behalf of the Higgs@FutureColliders working group

Open Symposium - Update of the European Strategy for Particle Physics
14th of May 2019
Introduction

♦ Higgs potential: $V(\Phi) = \frac{1}{2} \mu^2 \Phi^2 + \frac{1}{4} \lambda \Phi^4$

![Graph of Higgs potential]

♦ Approximation around the v.e.v:

$V(\Phi) \approx \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4$

- mass term
- self-coupling terms

♦ $\lambda$ known from v.e.v and Higgs mass: $\lambda = \frac{m^2}{2 \cdot v^2} \approx 0.13$

♦ BSM effects could change $\lambda \Rightarrow$ define deviation of tri-linear term: $\kappa_\lambda = \kappa_3 = \frac{\lambda_{HHH}}{\lambda_{SM}^{HHH}}$

- no quartic terms considered here

more details on the motivations in the talk by G. Servant
How to measure the tri-linear self-coupling
Main production mode: ggF

- destructive interference between triangle and box diagrams \( \Rightarrow \sigma(HH)/\sigma(H) = 0.1\% \)

Self-couplings through total HH cross section, and diff. cross section \( d\sigma/dm_{HH} \):
Path towards measuring the Higgs potential

Elisabeth Petit, CPPM, AMU/CNRS/IN2P3

Di-Higgs production: ee colliders

♦ Main production modes: ZHH and ννHH
  - ZHH
  ![ZHH diagram]
  - VBF ννHH
  ![VBF diagram]

♦ Self-couplings through HH cross-section at different √s + production modes + m_{HH}
  - ZHH stronger constraints for κ_λ > 1
  - ννHH stronger constraints for κ_λ < 1

![Graphs showing cross-sections and self-couplings]
Single-Higgs couplings (1)

♦ Higgs self-interaction via one-loop corrections of the single-Higgs production
  – $\kappa_\lambda$-dependent corrections to the tree-level cross-sections

♦ pp colliders:

♦ ee colliders:

♦ ex. for $\kappa_\lambda = 2$:
  – $\sigma(pp \to t\bar{t}H)$ modified by 3%
  – $\sigma(ee \to ZH)$ modified by 1%
More global view: SMEFT\textsubscript{ND}

Deformation of the single-Higgs + EW processes:

\[
\text{SMEFT}_{\text{ND}} \equiv \{ \delta m, c_{gg}, \delta c_{Z}, c_{\gamma\gamma}, c_{ZZ}, c_{\square}, \delta y_{t}, \delta y_{c}, \delta y_{b}, \delta y_{\tau}, \delta y_{\mu}, \lambda_{\ast} \} \\
+ \left\{ (\delta g_{Zu}^{Zd})_{q_i}, (\delta g_{Zd}^{Zu})_{q_i}, (\delta g_{Zv}^{Ze})_{\ell}, (\delta g_{Zu}^{Zu})_{q_i}, (\delta g_{Zd}^{Zd})_{q_i}, (\delta g_{Ze}^{Ze})_{\ell} \right\}_{q_1 \neq q_2, \ell = e, \mu, \tau}
\]

+ correction to the trilinear Higgs self-coupling: \( \delta \kappa_{\lambda} = \kappa_{\lambda} - 1 \)

Can also consider the effect of \( \delta \kappa_{\lambda} \) on the other parameters

- a few examples:

\[
\begin{align*}
\text{Higgs couplings variation along the flat direction} & \quad 1704.01953 \\
\text{variation [stand. dev.]} & \quad +3\sigma \\
\delta_{\kappa_{\lambda}} & \quad -3 \sigma \\
\end{align*}
\]

- could also affect EW precision observables at NNLO
How to measure deviations of $\lambda_3$

- The Higgs self-coupling can be assessed using **di-Higgs** production and **single-Higgs** production.
- The sensitivity of the various future colliders can be obtained using four different methods:

<table>
<thead>
<tr>
<th></th>
<th>di-Higgs</th>
<th>single-H</th>
</tr>
</thead>
<tbody>
<tr>
<td>exclusive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. di-H, excl.</td>
<td>• Use of $\sigma$(HH)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• only deformation of $\kappa\lambda$</td>
<td></td>
</tr>
<tr>
<td>global</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. di-H, glob.</td>
<td>• Use of $\sigma$(HH)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• deformation of $\kappa\lambda$ + of the single-H couplings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) do not consider the effects at higher order of $\kappa\lambda$ to single H production and decays</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(b) these higher order effects are included</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. single-H, excl.</td>
<td>• single Higgs processes at higher order</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• only deformation of $\kappa\lambda$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. single-H, glob.</td>
<td>• single Higgs processes at higher order</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• deformation of $\kappa\lambda$ + of the single Higgs couplings</td>
<td></td>
</tr>
</tbody>
</table>
Inputs from Future Colliders

*4

#152: HL-LHC
#160: HE-LHC
#135: FCC-hh

#29: CEPC
#145: CLIC
#77: ILC
#89: FCC-ee
Measure $\kappa_{\lambda}$ through HH: method 1

Either extrapolations from Run-2 analyses, or dedicated studies with smeared/parametric detector response, corresponding to pile-up of 200

### Systematic uncertainties: common agreement between ATLAS and CMS

- performance uncertainties scaled by 0.5 to 1
- theoretical uncertainties scaled by 0.5

<table>
<thead>
<tr>
<th>Process</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bbbb$</td>
<td>extrapolation</td>
<td>parametric</td>
</tr>
<tr>
<td>$bb\tau\tau$</td>
<td>extrapolation</td>
<td>parametric</td>
</tr>
<tr>
<td>$bbyy$</td>
<td>smearing</td>
<td>parametric</td>
</tr>
<tr>
<td>$bbVV$</td>
<td>parametric</td>
<td></td>
</tr>
<tr>
<td>$bbZZ$</td>
<td>parametric</td>
<td></td>
</tr>
</tbody>
</table>

- Largest BR 😊 Large multijet and tt bkg 😞
- Sizeable BR 😊 Relatively small bkg 😊
- Small BR 😞 Good diphoton resolution 😊 Relatively small bkg 😊
- Large BR 😊 Large bkg 😞
- Very small BR 😞 Very small bkg 😊

more details in the talk by P. Azzi
HL-LHC, HH measurements (2)

◊ General analysis strategy:
  - multivariate methods trained for observation of SM di-Higgs production
  - require candidate masses consistent with SM Higgs boson
  - use $m_{HH}$ distribution when possible

◊ NB: some inputs or systematics little known
  - multijet bkg modelling for $HH \rightarrow b\bar{b}b\bar{b}$
  - $\tau$ fake-rate
  - ...

⇒ room for improvement
HL-LHC, HH results

♦ Expected significance (SM) with and without systematics at HL-LHC

<table>
<thead>
<tr>
<th></th>
<th>Statistical-only</th>
<th>Statistical + Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ATLAS</td>
<td>CMS</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}bb$</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\tau\tau$</td>
<td>2.5</td>
<td>1.6</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\gamma\gamma$</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}VV (l\nu\nu)$</td>
<td>-</td>
<td>0.59</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}ZZ (4l)$</td>
<td>-</td>
<td>0.37</td>
</tr>
<tr>
<td>combined</td>
<td>3.5</td>
<td>2.8</td>
</tr>
<tr>
<td>Combined</td>
<td>4.5</td>
<td></td>
</tr>
</tbody>
</table>

4σ expected with ATLAS+CMS!

♦ Measurement of signal strength $\mu$ (SM):
  - $\sim 25\%$ (30\%) without (with) systematics
  - $\mu = 0$ (no SM HH signal) excluded at 95\% CL

♦ Measurement of $\kappa_\lambda$:
  - 68\% CI of 50\%
  - 2nd minimum excluded at 99.4\% CL thanks to the $m_{HH}$ shape information

ATLAS and CMS HL-LHC prospects

3 ab⁻¹ (14 TeV)

- Combination
- $b\bar{b}\gamma\gamma$
- $b\bar{b}\tau\tau$
- $b\bar{b}bb$
- $b\bar{b}ZZ(4l)$
- $b\bar{b}VV(l\nu\nu)$

SM HH significance: 4σ
0.1 < $\kappa_\lambda$ < 2.3 [95\% CL]
0.5 < $\kappa_\lambda$ < 1.5 [68\% CL]
Extrapolation of ATLAS HL-LHC results to HE-LHC: method 1
- scale cross-section to 27 TeV (*4) and luminosity to 15 ab⁻¹ (*5), no systematic uncertainties
- \(b\bar{b}\tau\tau\) channel: significance: 10.7\(\sigma\), precision on \(\kappa_\lambda\): 20%
- \(b\bar{b}\gamma\gamma\) channel: significance: 7.1\(\sigma\), precision on \(\kappa_\lambda\): 40%
  - pessimistic because analysis not optimised for measurement of \(\kappa_\lambda\)

Phenomenology study for \(b\bar{b}\gamma\gamma\): 15% precision on \(\kappa_\lambda\)
- realistic detector performance
- no pile-up considered (\(\mu=800-1000\))

Combination of channels: \(\kappa_\lambda\) could be measured with a 68% CI of 10 to 20%
Method (1)

Main channel: $b\bar{b}\gamma\gamma$
- Delphes simulation
- 2D likelihood fit of $m_{\gamma\gamma}$ vs $m_{HH}$
- scenarios with varying
  - photon efficiency
  - $m_{\gamma\gamma}$ resolution
  - background level
  - small effect (1-2%)
  $\Rightarrow$ 5-7% uncertainty on $\kappa_\lambda$

Other channels:

<table>
<thead>
<tr>
<th>Channel</th>
<th>$b\bar{b}\gamma\gamma$</th>
<th>$b\bar{b}ZZ^*[-\rightarrow 4\ell]$</th>
<th>$b\bar{b}WW^*[-\rightarrow 2j\ell\nu]$</th>
<th>4b+jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta\kappa_\lambda$</td>
<td>6.5%</td>
<td>14%</td>
<td>40%</td>
<td>30%</td>
</tr>
</tbody>
</table>

Determination of $\kappa_\lambda$ at the level of $O(5%)$ expected to be within the FCC reach
Method (1)

ZHH @ 500 GeV
- $Z \rightarrow l^+l^-/\nu\bar{\nu}/q\bar{q}$ and HH $\rightarrow b\bar{b}b\bar{b}/b\bar{b}WW$
- precision of 16.8% on the total cross section for $e^+e^- \rightarrow ZHH$
- 27% uncertainty on $\kappa_\lambda$

Also studies of $\nu\bar{\nu}HH @ 1$ TeV $\rightarrow 10\%$ uncertainty
Method (1)

- $\bar{\nu}\nu HH$ @ 1.4 and 3 TeV
  - full-simulation + BDT selection
  - Significance:
    - 1.4 TeV: 3.6$\sigma$
    - 3 TeV: $\sim$14$\sigma$

- $ZHH$ @ 1.4 TeV
  - extrapolation of 380 GeV full-sim performance
  - no background

Uncertainty on $\kappa_\lambda$:
- $m_{HH}$ or ZHH cross-section to lift the degeneracy

<table>
<thead>
<tr>
<th>Constraints for $\kappa_{HHH}$ based on</th>
<th>$\Delta \chi^2 = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH$\nu \bar{\nu}$ cross section only (3 TeV)</td>
<td>[0.90, 1.12] $\cup$ [2.40, 2.61]</td>
</tr>
<tr>
<td>HH$\nu \bar{\nu}$ (3 TeV) and ZHH (1.4 TeV) cross section</td>
<td>[0.90, 1.11]</td>
</tr>
<tr>
<td>HH$\nu \bar{\nu}$ differential (3 TeV)</td>
<td>[0.93, 1.12]</td>
</tr>
<tr>
<td>HH$\nu \bar{\nu}$ differential (3 TeV) and ZHH cross section (1.4 TeV)</td>
<td>[0.93, 1.11]</td>
</tr>
</tbody>
</table>
Methods (3) and (4) only

- CEPC, FCC-ee@240 GeV, ILC@250 GeV
- FCC-ee@365 GeV, ILC@350 GeV, CLIC@380 GeV

Based on very good precision on cross-section, e.g. CEPC and FCC-ee240:
- $\sigma(ZH): 0.5\%$
- $\sigma(\nu\nu H): 2-3\%$
- ex.: $\sigma(ZH)$ modified by 1% for $\kappa_\lambda =2$
  $\Rightarrow 2\sigma$ sensitivity

Additional sensitivity from combining different $\sqrt{s}$
- allows for a reduction of the uncertainty on other EFT parameters, removing correlations in the global fit
Additional inputs (not in the report)

♦ **electron-proton** colliders: LHeC and FCC-eh
  - FCC-eh di-Higgs:
    - $0.83 < \kappa_\lambda < 1.24$ @3.5 TeV
    - $0.88 < \kappa_\lambda < 1.14$ @5 TeV
  - FCC-eh single-Higgs: missing the 1-loop dependence on $k_\lambda$
    - can’t apply Methods (3) and (4)

♦ **muon** colliders
  - preliminary projections
  - $\sqrt{s} = 10, 14, 30$ TeV
  - $HH \rightarrow 4b$: measurement of $\kappa_\lambda^3$: 3% at 10 TeV, 1% at 30 TeV

♦ **Quartic term $\lambda_4$**
  - $2\sigma$ at FCC-hh, $\kappa_\lambda^4$ in $[-4; +16]$ at 95% CL
  - muon collider @ 30 TeV: $0.8 < \kappa_\lambda^4 < 1.5$ at 68% CL (if $\kappa_\lambda^3 = 1$)
Comparisons and combination by the Higgs@FC working group
Inputs and methodology

Summary of inputs:

<table>
<thead>
<tr>
<th></th>
<th>√s</th>
<th>HH measurements</th>
<th>single-Higgs couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HL-LHC</td>
<td>14 TeV</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>27 TeV</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>FCC-hh/eh/ee</td>
<td>100 TeV</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>ee</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CEPC</td>
<td>240 GeV</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>ILC250</td>
<td>250 GeV</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>ILC350</td>
<td>250 + 350 GeV</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>ILC500</td>
<td>250 + 350 + 500 GeV</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>CLIC380</td>
<td>380 GeV</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>CLIC1500</td>
<td>380 GeV + 1.5 TeV</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>CLIC3000</td>
<td>380 GeV + 1.5+3 TeV</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>FCC-ee240</td>
<td>240 GeV</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>FCC-ee365</td>
<td>240 + 365 GeV</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

Compute the uncertainty on $\kappa$ using the four methods:

- Method (1) : recomputed to validate the method, good agreement
- Method (2) : combination of HH inputs and single-Higgs couplings with SMEFT (when possible)
- Methods (3) and (4) : single-Higgs couplings (SMEFT) + combination with HL-LHC HH results (50% uncertainty)
68% CL uncertainties on $\kappa_3$ with the four methods:
Results: using di-Higgs production

♦ 68% CL uncertainties on $\kappa_\lambda$:

![Graph showing 68% CL bounds on $\kappa_3$ for various collider scenarios.

May 2019]

♦ Constraints set by the HH production (method (1)) strong enough that small impact of a global analysis (method (2))
  - FCC-hh: 1% uncertainty on the top Yukawa coupling $\Rightarrow$ deviation of HH rate at a level comparable to the uncertainty on $\kappa_\lambda$
Results: using single-Higgs measurements

- 68% CL uncertainties on $\kappa_\lambda$:

- Methods (3) and (4) particularly relevant for low-energy colliders below the HH production threshold
  - above this, can still be relevant to complement results from the HH analysis: lift degeneracy + improve 95% CL limit

- Importance of global analysis, ie Method (4), to get robust results
Results: comparison of results

- 68% CL uncertainties on $\kappa_\lambda$ with Methods (1) and (4):

![Graph showing 68% CL bounds on $\kappa_3$ (%)]

- **HL-LHC** will exclude the absence of the Higgs self-interaction at 95%CL
- Several of the proposed FCs will reach a sensitivity of $\sim 20%$ ⇒ establish the existence of the self-interaction at $5\sigma$
- **CLIC3000/FCC-hh** can reach a sensitivity of $\sim 10%/5%$ ⇒ can start probing the size of the quantum corrections to the Higgs potential directly
**Conclusion**

- State of the art prospective measurement of the **tri-linear coupling** at Future Colliders through the HH and single-Higgs production

- HL-LHC: $4\sigma$ evidence of the HH process + 50% uncertainty on $\kappa$.

- Sensitivity from Future Colliders and combination with HL-LHC
  - possible to establish the existence of the self-coupling at $5\sigma$ for several FCs

- Complementary of Methods to understand possible deviations from the SM

- Report from the *Higgs@FC* working group on arxiv: 1905.03764
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HL-LHC</td>
<td>$^{+60}_{-50}%$ (50%)</td>
<td>52%</td>
<td>46%</td>
<td>50%</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>10-20% (n.a.)</td>
<td>n.a.</td>
<td>41%</td>
<td>50%</td>
</tr>
<tr>
<td>ILC$_{250}$</td>
<td>−</td>
<td>−</td>
<td>28%</td>
<td>49%</td>
</tr>
<tr>
<td>ILC$_{350}$</td>
<td>−</td>
<td>−</td>
<td>28%</td>
<td>47%</td>
</tr>
<tr>
<td>ILC$_{500}$</td>
<td>27% (27%)</td>
<td>27%</td>
<td>26%</td>
<td>37%</td>
</tr>
<tr>
<td>CLIC$_{380}$</td>
<td>−</td>
<td>−</td>
<td>45%</td>
<td>50%</td>
</tr>
<tr>
<td>CLIC$_{1500}$</td>
<td>36% (36%)</td>
<td>36%</td>
<td>40%</td>
<td>49%</td>
</tr>
<tr>
<td>CLIC$_{3000}$</td>
<td>$^{+11}_{-7}%$ (n.a.)</td>
<td>n.a.</td>
<td>35%</td>
<td>49%</td>
</tr>
<tr>
<td>FCC-ee$_{240}$</td>
<td>−</td>
<td>−</td>
<td>19%</td>
<td>48%</td>
</tr>
<tr>
<td>FCC-ee$_{365}$</td>
<td>−</td>
<td>−</td>
<td>19%</td>
<td>34%</td>
</tr>
<tr>
<td>FCC-ee/ch/eh hh</td>
<td>5% (5%)</td>
<td>6%</td>
<td>18%</td>
<td>25%</td>
</tr>
<tr>
<td>CEPC</td>
<td>−</td>
<td>−</td>
<td>17%</td>
<td>49%</td>
</tr>
</tbody>
</table>

**Table 11.** Sensitivity at 68% probability on the Higgs cubic self-coupling at the various FCs. All the numbers reported correspond to a simplified combination of the considered collider with HL-LHC which is approximated by a 50% constraint on $\kappa_3$. The numbers in the first column (i.e. "di-H excl." or Method (1)) correspond to the results given by the future collider collaborations and in parenthesis, we report our derived estimate obtained in the binned analysis described in the text. In the three last columns, i.e. Methods (2a), (3) and (4), we report the results computed by the Higgs@FC working group. For the leptonic colliders, the runs are considered in sequence. For the colliders with $\sqrt{s} \lesssim 400$ GeV, Methods (1) and (2.a) cannot be used, hence the dash signs in the corresponding cells. No sensitivity was computed along Method (2.a) for HE-LHC and CLIC$_{3000}$ but our initial checks do not show any difference with the sensitivity obtained for Method (1). Due to the lack of results available for the $ep$ cross section in SMEFT, we do not present any result for LHeC nor HE-LHeC.
# Future colliders

<table>
<thead>
<tr>
<th>Collider</th>
<th>type</th>
<th>√s [GeV]</th>
<th>∆P [%]</th>
<th>N(Det.)</th>
<th>L_{ini} [10^{34} \text{cm}^{-2}\text{s}^{-1}]</th>
<th>L [ab^{-1}]</th>
<th>time [years]</th>
<th>Refs</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC-ee240</td>
<td>ee</td>
<td>M_Z</td>
<td>0/0</td>
<td>2</td>
<td>100/200</td>
<td>150.0</td>
<td>4</td>
<td>[1]</td>
<td>FCC-ee240</td>
</tr>
<tr>
<td>FCC-ee356</td>
<td>ee</td>
<td>2M_W</td>
<td>2/2</td>
<td>2</td>
<td>25</td>
<td>10.0</td>
<td>1-2</td>
<td></td>
<td>FCC-ee356</td>
</tr>
<tr>
<td></td>
<td>ee</td>
<td>240 GeV</td>
<td>0/0</td>
<td>2</td>
<td>7</td>
<td>5.0</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ee</td>
<td>2m_{top}</td>
<td>0/0</td>
<td>2</td>
<td>0.8/1.4</td>
<td>1.5</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILC</td>
<td>ee</td>
<td>250 GeV</td>
<td>±80/0/30</td>
<td>1</td>
<td>1.35/2.7</td>
<td>2.0</td>
<td>11.5</td>
<td>[3, 11]</td>
<td>ILC_{250}</td>
</tr>
<tr>
<td>ILC</td>
<td>ee</td>
<td>350 GeV</td>
<td>±80/0/30</td>
<td>1</td>
<td>1.6</td>
<td>0.2</td>
<td>1</td>
<td></td>
<td>ILC_{350}</td>
</tr>
<tr>
<td>ILC</td>
<td>ee</td>
<td>500 GeV</td>
<td>±80/0/30</td>
<td>1</td>
<td>1.8/3.6</td>
<td>4.0</td>
<td>8.5</td>
<td></td>
<td>ILC_{500}</td>
</tr>
<tr>
<td>CEPC</td>
<td>ee</td>
<td>M_Z</td>
<td>0/0</td>
<td>2</td>
<td>17/32</td>
<td>16.0</td>
<td>1</td>
<td>[2]</td>
<td>CEPC</td>
</tr>
<tr>
<td>CEPC</td>
<td>ee</td>
<td>2M_W</td>
<td>0/0</td>
<td>2</td>
<td>10</td>
<td>2.6</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CEPC</td>
<td>ee</td>
<td>240 GeV</td>
<td>0/0</td>
<td>2</td>
<td>3</td>
<td>5.6</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLIC</td>
<td>ee</td>
<td>380 GeV</td>
<td>±80/0/30</td>
<td>1</td>
<td>1.0</td>
<td>1.0</td>
<td>8</td>
<td>[12]</td>
<td>CLIC_{380}</td>
</tr>
<tr>
<td>CLIC</td>
<td>ee</td>
<td>1.5 TeV</td>
<td>±80/0/30</td>
<td>1</td>
<td>3.7</td>
<td>2.5</td>
<td>7</td>
<td></td>
<td>CLIC_{1500}</td>
</tr>
<tr>
<td>CLIC</td>
<td>ee</td>
<td>3.0 TeV</td>
<td>±80/0/30</td>
<td>1</td>
<td>6.0</td>
<td>5.0</td>
<td>8</td>
<td></td>
<td>CLIC_{3000}</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1 y SD before 2m_{top} run)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHeC</td>
<td>ep</td>
<td>1.3 TeV</td>
<td>-</td>
<td>1</td>
<td>0.8</td>
<td>1.0</td>
<td>15</td>
<td>[9]</td>
<td>LHeC</td>
</tr>
<tr>
<td>HE-LHeC</td>
<td>ep</td>
<td>2.6 TeV</td>
<td>-</td>
<td>1</td>
<td>1.5</td>
<td>2.0</td>
<td>20</td>
<td>[1]</td>
<td>HE-LHeC</td>
</tr>
<tr>
<td>FCC-eh</td>
<td>ep</td>
<td>3.5 TeV</td>
<td>-</td>
<td>1</td>
<td>1.5</td>
<td>2.0</td>
<td>25</td>
<td>[1]</td>
<td>FCC-eh</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>T_0</th>
<th>+5</th>
<th>+10</th>
<th>+15</th>
<th>+20</th>
<th>...</th>
<th>+26</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5/ab</td>
<td></td>
<td></td>
<td>1.5/ab</td>
<td></td>
<td>1.0/ab</td>
<td></td>
</tr>
<tr>
<td></td>
<td>250 GeV</td>
<td></td>
<td></td>
<td>250 GeV</td>
<td></td>
<td>250 GeV</td>
<td></td>
</tr>
<tr>
<td>CEPC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.6/ab</td>
<td></td>
<td></td>
<td>16/ab</td>
<td></td>
<td>2.5/ab</td>
<td></td>
</tr>
<tr>
<td></td>
<td>240 GeV</td>
<td></td>
<td></td>
<td>2M_W</td>
<td></td>
<td>2M_W</td>
<td></td>
</tr>
<tr>
<td>CLIC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0/ab</td>
<td></td>
<td></td>
<td>2.5/ab</td>
<td></td>
<td>5.0/ab</td>
<td></td>
</tr>
<tr>
<td></td>
<td>380 GeV</td>
<td></td>
<td></td>
<td>380 GeV</td>
<td></td>
<td>380 GeV</td>
<td></td>
</tr>
<tr>
<td>FCC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>150/ab</td>
<td></td>
<td></td>
<td>10/ab</td>
<td></td>
<td>1.7/ab</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ee, M_Z</td>
<td></td>
<td></td>
<td>ee, 2M_W</td>
<td></td>
<td>ee, 2M_W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ee, 240 GeV</td>
<td></td>
<td></td>
<td>ee, 2M_W</td>
<td></td>
<td>ee, 2M_W</td>
<td></td>
</tr>
<tr>
<td>LHeC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.06/ab</td>
<td></td>
<td></td>
<td>0.2/ab</td>
<td></td>
<td>0.72/ab</td>
<td></td>
</tr>
<tr>
<td>HE-LHC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10/ab per experiment in 20γ</td>
<td></td>
<td></td>
<td>10/ab per experiment in 20γ</td>
<td></td>
<td>10/ab per experiment in 20γ</td>
<td></td>
</tr>
<tr>
<td>FCC-eh/hh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20/ab per experiment in 25γ</td>
<td></td>
<td></td>
<td>20/ab per experiment in 25γ</td>
<td></td>
<td>20/ab per experiment in 25γ</td>
<td></td>
</tr>
<tr>
<td>Notre-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dame-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>de-Paris</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Comparison to HL-LHC 2014 results

♦ ECFA High Luminosity LHC Experiments Workshop in 2014
♦ ggF cross-section: \(40.2 \text{ fb} \, [\text{NNLO}] \to 36.69 \text{ fb} \, [\text{NNLO calculation with finite } m_t \text{ effects at NLO}]\)
♦ \(b\bar{b}\gamma\gamma\) and \(b\bar{b}WW\), no \(b\bar{b}\tau\tau\) nor \(b\bar{b}bb\)
♦ Expected significance:
  - \(~1.3\sigma\) for \(b\bar{b}\gamma\gamma\)

♦ Since then:
  - TDR of the Phase-II upgrades: improvement of performance
    • particle identification, energy resolution, trigger, …
  - large use of MVA selection
  - better understanding of extrapolation of uncertainties
### Expected HH results at HL-LHC

<table>
<thead>
<tr>
<th>HH final state</th>
<th>ATLAS Significance Coupling limit (95% C.L.)</th>
<th>CMS Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH → bbyγ</td>
<td>$1.05 \sigma$ [-0.8 &lt; \frac{\lambda_{HHH}}{\lambda_{SM}} &lt; 7.7]</td>
<td>$1.43 \sigma$</td>
</tr>
<tr>
<td>HH → bbττ</td>
<td>$0.6 \sigma$ [-4.0 &lt; \frac{\lambda_{HHH}}{\lambda_{SM}} &lt; 12.0]</td>
<td>$0.39 \sigma$</td>
</tr>
<tr>
<td>HH → bbb</td>
<td>$0.39 \sigma$ [-3.5 &lt; \frac{\lambda_{HHH}}{\lambda_{SM}} &lt; 11.0]</td>
<td>$0.39 \sigma$</td>
</tr>
<tr>
<td>HH → bbVV</td>
<td></td>
<td>$0.45 \sigma$</td>
</tr>
<tr>
<td>ttHH, HH→ bbb</td>
<td>$0.35 \sigma$</td>
<td></td>
</tr>
</tbody>
</table>

**2018 Yellow Report:**

**Improved results already in the pipeline (especially for HL-LHC TDRs)**

S. Jézéquel, HL-LHC/HE-LHC Workshop 2017
The sensitivity of the various future colliders to the Higgs cubic coupling can be obtained using four different methods:

1. an exclusive analysis of HH production, i.e., a fit of the double Higgs cross section considering only deformation of the Higgs cubic coupling;

2. a global analysis of HH production, i.e., a fit of the double Higgs cross section considering also all possible deformations of the single Higgs couplings that are already constrained by single Higgs processes;
   - (a) the global fit does not consider the effects at higher order of the modified Higgs cubic coupling to single Higgs production and to Higgs decays;
   - (b) these higher order effects are included;

3. an exclusive analysis of single Higgs processes at higher order, i.e., considering only deformation of the Higgs cubic coupling;

4. a global analysis of single Higgs processes at higher order, i.e., considering also all possible deformations of the single Higgs couplings.
Mandate of the Higgs@FC working group

Mandate agreed by RECFA in consultation with the PPG
“Higgs physics with future colliders in parallel and beyond the HL-LHC”

- In the context of exploring the Higgs sector, provide a coherent comparison of the reach with all future collider programmes proposed for the European Strategy update, and to project the information on a timeline.
- For the benefit of the comparison, motivate the choice for an adequate interpretation framework (e.g. EFT, κ, ...) and apply it, and map the potential prerequisites related to the validity and use of such framework(s).
- For at least the following aspects, where achievable, comparisons should be aim for:
  - Precision on couplings and self-couplings (through direct and indirect methods)
  - Sensitivities to anomalous and rare Higgs decays (SM and BSM), and precision on total width
  - Sensitivity to new high-scale physics through loop corrections
  - Sensitivities to flavor violation and CP violating effects
- In all cases the future collider information is to be combined with the expected HL-LHC reach, and the combined extended reach is to be compared with the baseline reach of the HL-LHC.
- In April 2019, provide a comprehensive and public report to inform the community.

- Towards the Open Symposium the working group will work together with the PPG and provide a comprehensive and public report to inform the community, i.e. this is not an ECFA report
- The working group has a scientific nature, i.e. not a strategic nature, it uses the input submitted to the Strategy process to map the landscape of Higgs physics at future colliders
- The “convenors” in the PPG who are connected to this specific topic (Beate Heinemann and Keith Ellis) and the ECFA chair (Jorgen D’Hondt) will be included as ex-officio observers, i.e. included in the working group communications and discussions
Effective lagrangian: $\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \frac{1}{\Lambda^3} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \cdots$, $\mathcal{L}_d = \sum_i c_i^{(d)} \mathcal{O}_i^{(d)}$.

Higgs couplings to vector bosons:
- only $c_{gg}$, $\delta c_{Z}$, $c_{\gamma\gamma}$, $c_{Z\gamma}$, $C_{ZZ}$, $c_{Z\Box}$ independent parameters

$$\Delta \mathcal{L}_6^{hVV} = \frac{h}{v} \left[ 2\delta c_w m_W^2 W^+_{\mu} W^-_{\mu} + \delta c_z m_Z^2 Z^+_{\mu} Z^-_{\mu} 
+ c_{ww} \frac{g^2}{2} W^+_{\mu} W^-_{\mu} + c_{w\Box} g^2 (W^-_{\mu} \partial_{\nu} W^+_{\mu} + \text{h.c.}) 
+ c_{gg} \frac{g_s}{4} G^a_{\mu \nu} G^a_{\nu \mu} + c_{\gamma\gamma} \frac{e^2}{4} A_{\mu \nu} A_{\mu \nu} + c_{Z\gamma} \frac{e \sqrt{g^2 + g'^2}}{2} Z^+_{\mu \nu} A_{\mu \nu} + \frac{g^2 + g'^2}{4} Z_{\mu \nu} Z_{\mu \nu} 
+ c_{Z\Box} g^2 Z^+_{\mu} \partial_{\nu} Z^-_{\mu} + c_{\Box} g g' Z^+_{\mu} \partial_{\nu} A_{\mu \nu} \right] .$$

Tri-linear gauge couplings:

$$\Delta \mathcal{L}_6^{aTGC} = i e \delta \kappa_{t} A_{\mu}^\nu W^+_{\mu} W^-_{\nu} + i g \cos \theta_{w} \left[ \delta g_{1Z} (W^+_{\mu} W^-_{\nu} - W^-_{\mu} W^+_{\nu}) Z^\nu + (\delta g_{1Z} - \frac{g'^2}{g^2} \delta \kappa_{t}) Z_{\mu \nu} W^+_{\mu} W^-_{\nu} \right]$$

$$+ \frac{i g \lambda_{t}}{m_W^2} \left( \sin \theta_{w} W^+_{\mu} W^-_{\nu} A_{\rho}^\mu + \cos \theta_{w} W^+_{\mu} W^-_{\nu} Z_{\rho}^\mu \right) ,$$

Yukawa couplings: $\Delta \mathcal{L}_6^{hff} = -\frac{h}{v} \sum_{f \in u,d,e} \hat{\delta}_{y_{f}} m_{f} \bar{f} f + \text{h.c.}$

Neutral diagonality.
Extrapolation from Run-2 analysis
- fit of $m_{4j}$ distribution
- $p_T^{jet} > 40$ GeV, different thresholds tested

**ATLAS Preliminary**
Projection from Run 2 data
\[ \sqrt{s} = 14 \text{ TeV}, 3000 \text{ fb}^{-1} \]

HH$\rightarrow$b$b$b$b
2016 analysis systematic uncertainties

Systematics
- dominated by multijet data-driven model
- conservative assumption: Run-2 systematics used

Significance:
1.4/0.61\sigma without/with syst
SM signal + BSM benchmark points

Resolved and boosted b-jets
  - boosted topologies more sensitive to BSM scenarios where high $m_{HH}$ is enhanced

Resolved:
  - $p_T > 45$ GeV, different thresholds tested
  - BDT against multijet bkg + $t\bar{t}$ and single-Higgs

Small uncertainty considered for multijet background

Significance:
  - $1.2\sigma$ wo/syst
  - $0.95\sigma$ w/ syst
Extrapolation from Run-2 analysis

Three signal regions:
- $\tau_{\text{lep}} \tau_{\text{had}}$ (Single Lepton Trigger)
- $\tau_{\text{lep}} \tau_{\text{had}}$ (Lepton Tau Trigger)
- $\tau_{\text{had}} \tau_{\text{had}}$ (Single Tau Trigger and Di-Tau Trigger)

BDT output used as final discriminant
- binning adapted to higher statistics

Limit on $\kappa_\lambda$: LTT category not included and dedicated BDT trained on $\kappa_\lambda = 20$

Different assumptions for systematics

Significance: $2.5/2.1\sigma$ without/with syst
3 categories: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$

Use of a neural network
- 27 basic + 21 reconstructed + 4 global features
- deep learning techniques, with optimal data preprocessing, study of the activation functions, and data augmentation

Simultaneous fit of the NN output for the 3 decay channels
- discriminant binned per decay channel via adaptive binning

Significance: $1.6/1.4\sigma$ without/with syst
The document contains several bullet points discussing the analysis and significance of a specific Higgs decay channel, $\text{HH} \to \bar{b}b\gamma\gamma$ (ATLAS).

- **Dedicated analysis with smearing functions**: upgraded detector geometry and performance functions
  - $m_{\gamma\gamma}$ resolution $\sim 1.6$ GeV

- **Dedicated BDT** trained to remove continuum background and main single-Higgs background ($t\bar{t}H$)

- **Limit on $\kappa_{\lambda}$**: use of the $m_{\bar{b}b\gamma\gamma}$ distribution for events with $123 < m_{\gamma\gamma} < 127$ GeV

- **Systematics**: very small impact in general

- **Significance**: $2.1/2.0\sigma$ without/with syst
Dedicated BDT to reject $t\bar{t}H$
- 75% reduction for 90% signal efficiency

Classification of events based on $M_x = m_{jj\gamma\gamma} - m_{\gamma\gamma} - m_{jj} + 250$ GeV into low and high mass categories

MVA event categorisation BDT to separate background and HH signal into medium (MP) and high (HP) purity

Fit of $m_{\gamma\gamma} \times m_{jj}$

Significance: $1.8/1.8\sigma$ without/with syst
- difference with ATLAS partly due to $m_{\gamma\gamma}$ resolution
Optimised on WW, but ZZ signal included for the results

Large irreducible backgrounds: \( \bar{t}t \), DY

Neural Network discriminant
- 9 input angular and mass variables
- signal extracted from the NN output (3 categories ee, \( \mu\mu \), e\( \mu \))

Results: 0.6\( \sigma \) significance
Very rare but **clean final** state, yet unexplored at the LHC

- Powerful $H\to 4\ell$ signature $\Rightarrow$ single Higgs dominant background

- Select events with $m_{4\ell}$ compatible with $m_H$

- Counting experiment with events around $m_H$

- $\sim 1$ signal event after selection
  - $S/B \sim 0.1$

- Results: $0.4\sigma$ significance
♦ Comparison of negative log-likelihood ratios:

**ATLAS and CMS** 3000 fb⁻¹ (14 TeV)

**Diagram 1:**
- **HL-LHC prospects**
- Blue line: ATLAS
- Red line: CMS
- Black line: Combination

**Diagram 2:**
- **HL-LHC prospects**
- Blue line: b\(\bar{b}b\bar{b}\) (ATLAS)
- Blue line: b\(\bar{b}\)\(\tau\) (CMS)
- Green line: b\(bb\)VV (ATLAS)
- Green line: b\(bb\)\(\gamma\gamma\) (CMS)
- Orange line: b\(bbZZ^\ast(4l)\) (ATLAS)

♦ Difference on 2\(^{nd}\) minimum mainly from the b\(\bar{b}\)\(\gamma\gamma\) channel: 3 categories of m\(_{HH}\) (especially a low-m\(_{HH}\) one) to remove the degeneracy around \(\kappa_\lambda=6\) (while this low-m\(_{HH}\) category has no effect around 1)

♦ CMS slightly better below 1: b\(\bar{b}b\bar{b}\) + other smaller channels
Combined results (ATLAS+CMS)

♦ 68% CI, channel by channel
♦ Dashed line = no ATLAS analysis, using value from CMS (as for Higgs couplings)

κ measured with a precision of 50%
HL-LHC, via single-Higgs

♦ Inputs:
  - production modes → using projections of couplings measurements
  - kinematics properties of the event, here $p_T^{Higgs}$ in the $ttH(\rightarrow\gamma\gamma)$ channel

♦ Results:
  - dotted = method 3
  - solid = method 4
  - band = scenarios for systematics
♦ Channels: HH→bqbq and HH→bqbWW(→qqqq), second almost no effect

♦ BDT observables
  - angular distance and invariant mass of the Higgs candidates
  - flavour-tagging information
  - \( m_{HH} \)
  - \( E_T^{\text{miss}}, N_{\text{photons}}, \max (\eta_{\text{jets}}) \)

♦ Significance:
  - 1.4 TeV: 3.6\( \sigma \), 28% uncertainty
  - 3 TeV: \( \sim 14\sigma \), 7.3% uncertainty

♦ Effect of systematics negligible
CLIC, more info

- Channels: HH→b̅b̅b̅b̅ and HH→b̅b̅WW(→q̅q̅q̅q̅), second almost no effect
- BDT observables
  - angular distance and invariant mass of the Higgs candidates
  - flavour-tagging information
  - $m_{HH}$
  - $E_T^{miss}$, $N_{photons}$, max $(\eta_{jets})$
- Significance:
  - 1.4 TeV: 3.6σ, 28% uncertainty
  - 3 TeV: ~14σ, 7.3% uncertainty
- Effect of systematics negligible
Single-Higgs couplings (1)

- Higgs self-interaction via **one-loop corrections** of the single-Higgs production
  - $\kappa_\lambda$-dependent **corrections** to the tree-level cross-sections

- **pp colliders**

- **ee colliders**
68% and 95% CI on the measurement of $\kappa_\lambda$:

- also include results with single-Higgs cross-section (method (3) and (4))

The 50% uncertainty from HL-LHC method (1) baseline for combination with other Future Colliders
Inputs to the European strategy update

♦ #152: The physics potential of HL-LHC
♦ #160: The physics potential of HE-LHC
♦ #135: Future Circular Collider - The Integrated Programme (FCC-int)
♦ #29: CEPC Input to the ESPP 2018 - Physics and Detector
♦ #145: The Compact Linear e+e− Collider (CLIC): Physics Potential
♦ #77: The International Linear Collider. A Global Project