Measuring Higgs self-coupling at the FCC

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Michele Selvaggi (CERN)

also based on:
[1606.09408], [1802.01607],
[1809.10041]

FCC week 2019 - 27/06/2019 - Bruxelles
Why measure HH?

- Measurement of HH gives access to the magnitude of the Higgs self-interaction:

\[ V = \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 \]

- Higgs trilinear coupling constant \( \lambda \) only depends on the Higgs field VEV and Higgs mass. Purely determined by EWSB (in the SM).

- Shape of the Higgs potential is determined by the self coupling value (EWPT).
Prospects for HH measurements

1) LHC
   • $O(10)$ - $O(3)$
   • Could detect large anomalous coupling

2) HL-LHC
   • $O(1)$
   • Potential for evidence (3σ precision)

3) FCC-ee: single H couplings + indirect measurement
   • Potential for observation (5σ precision)

4) FCC-hh: precision measurement

References:
- ATLAS Preliminary
- CMS
- CMS Phase-2
Measuring the Higgs self-coupling at FCC-ee

- High precision measurement of Higgs BR

- Large Luminosity, high precision on single Higgs couplings
  - Possible to determine Higgs self coupling via indirect measurement

- A 100% modification of the Higgs self-coupling changes the HZ cross section by 2% at 240 GeV and 0.5% at 365 GeV

McCullough [1312.3322]
DeVita et al.[1711.033978]
Higgs trilinear coupling at FCC-ee

- If all other SM coupling fixed (in particular HHVV, HVV coupling):
  - $\delta \kappa_\lambda \approx 12\%$ (2 IPs - baseline FCC-ee)
  - $\delta \kappa_\lambda \approx 9\%$ (4 IPs)

- Single Higgs cross section at loop level depends on HVV and HHVV:
  - At least two energy points lift the degeneracy

- With baseline design, 2 IPs, 15 years at $\sqrt{s}=90+160+240+350+365$ GeV
  - $\delta \kappa_\lambda \approx 42\%$ (34% combined with HL-LHC)
    - To be compared with 30 years of ILC$_{250+500}$

- With 4 IPs and 15 years of running:
  - $\delta \kappa_\lambda \approx 25\%$ (21% combined with HL-LHC)
    - To be compared with 15 years of CLIC$_{380+1500}$
    - 5$\sigma$ sensitivity by 2050

Blondel and Janot [1809.10041]
Higgs self-coupling at FCC-hh

- Very small cross-section due to negative interference with box diagram
- HL-LHC projections: $\delta k_\lambda / k_\lambda \approx 50$-100%
- Expect large improvement at FCC-hh:
  - $\sigma(100 \text{ TeV}) / \sigma(14 \text{ TeV}) \approx 40$ (and Lx10)
  - x400 in event yields and x20 in precision
- main channels studied:
  - $bb\gamma\gamma$ (golden channel)
  - $bbZZ(4l)$
  - $bbbj$
  - $bb\tau\tau$

G. Heinrich et al [1608.04798]
HH@ FCC-hh: production at 100 TeV and decay

• Higher order in QCD helps $\lambda$-dependent K-factor sensitivity (not only the rate)
  → included here ($bb\gamma\gamma, bbZZ$)!

G. Heinrich et al [1608.04798]

Higgs decay branching fraction

<table>
<thead>
<tr>
<th>$\delta K_{\lambda}/K_{\lambda}$</th>
<th>4b</th>
<th>WWbb</th>
<th>$\tau\tau bb$</th>
<th>$WWWW$</th>
<th>ZZbb</th>
<th>$\gamma\gamma bb$</th>
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<tbody>
<tr>
<td>30-40%</td>
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<td>20-30%</td>
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<td>5-10%</td>
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<tr>
<td>5%</td>
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FCC-hh Simulation (Delphes) = 100 TeV s$^{-1}$

$\lambda/\lambda_{obs}$ = $\lambda_{SM}$

$\ln L \Delta^2$
HH → bbγγ

- Large QCD backgrounds (jjγγ and γ+jets)
- Main difference w.r.t LHC is the very large ttH background
- Strategy:
  - exploit correlation of means in (m_γγ, m_{hh}) in signal
  - build a parametric model in 2D
  - perform a 2D Likelihood fit on the coupling modifier k_{λ}
  - δk_{λ} / k_{λ} = 5-7% (stat - stat+syst.) in this channel alone
HH → 4b+j boosted

- Large rates allow to look for boosted HH recoiling against a jet (low $m_{HH}$ drives the sensitivity)
- Relies on identification of two boosted Higgs-jets
- Fit the di-jet mass spectrum dominated by the large QCD background
- $\delta k_\lambda / k_\lambda = 20-40\%$ depending on assumed background rate
**HH → bb4l**

- **New channel** opening at FCC-hh!!
- clean channel with mostly reducible backgrounds (single Higgs)
- Simple cut and count analysis on (4e, 4μ and 2e2μ channels)

**Backgrounds:**
- $t\bar{t}H$, $H \rightarrow 4$ leptons
- $4l + \text{jets}$ ($ZZ^*$, $Z^*Z^*$, $ZZ$) continuum
- $p p \rightarrow H b \bar{b} \rightarrow 4l bb$

$\delta k_\lambda / k_\lambda = 15\text{-}20\%$

depending on systematics assumptions
bbWW → bblvqq

**Method:**
- $80 < m_{bb} < 150$ GeV
- $p_T(WW) > 150$ GeV
- BDT

**Backgrounds:**
- ttbar → bbWW
- V+jets

![Graphs and plots showing signal efficiency, background rejection, and BDT response distributions with statistical uncertainties.](image-url)
bbττ

PRELIMINARY !!!
The bbττ channel

- Exploit large branching ratio
  \[ 2 \times \text{BR}(H \to bb) \times \text{BR}(H \to \tau\tau) \approx 7.3\% \]

- Final states: both τ_{lep}τ_{had} and τ_{had}τ_{had} considered:

- Backgrounds:
  - Top pair
  - Single Higgs (VH, ttH, ggH)
  - Z + bb → ττ + bb

- τ_{lep}τ_{had} has larger B contamination
  - ttbar with τ_{had} + e/mu (in addition to τ_{lep}τ_{had})

Detector assumptions:

- No Pile-up
- Nominal FCC-hh detector resolutions:
  - b-tagging: \( \varepsilon_b = 85\% \), \( \varepsilon_{j \to b} = 1\% \) (≈ HL-LHC)
  - τ-tagging: \( \varepsilon_\tau = 80\% \), \( \varepsilon_{j \to \tau} = 1\% \). (≈ HL-LHC)
Preselection $\tau_{\text{had}}\tau_{\text{had}}$

- Simple preselection:
  - At least two $\tau$-tagged jets with:
    - $p_T(\tau_{\text{had}}) > 45$ GeV, $|\eta(\tau_{\text{had}})| < 3.0$
  - At least two $b$-tagged jets with:
    - $p_T(b) > 30$ GeV, $|\eta(b)| < 3.0$
  - Lepton-veto ($p_T(l) > 25$ GeV, $|\eta(l)| < 3.0$)

DISCRIMINATING VARIABLES

- $m_{bb}$
- $m_{\tau\tau}$
- $m_{hh}$
- $m_{T2}$
Preselection $\tau_{\text{had}} \tau_{\text{lep}}$

- Simple preselection:
  - One hadronic $\tau$-tagged jet with:
    - $p_T(\tau_{\text{had}}) > 45$ GeV, $|\eta(\tau_{\text{had}})| < 3.0$
  - At least two b-tagged jets with:
    - $p_T(b) > 30$ GeV, $|\eta(b)| < 3.0$
  - Exactly one lepton
    - $(p_T(l) > 25$ GeV, $|\eta(l)| < 3.0)$

smaller S/B
BDT training - $\tau_{\text{had}}\tau_{\text{had}}$

- **BDT** training input:
  - 4-vectors of $\tau_1$, $\tau_2$, $b_1$, $b_2$
  - 4-vectors of $H_{\tau\tau}$, $H_{bb}$, $HH$
  - $E_T^{\text{miss}}$
  - $M_{T2}$, $M_T(\tau_1)$, $M_T(\tau_2)$, $H_T$

- **Final Selection:**
  - $100 < m_{bb} < 130$ GeV
  - $80 < m_{\tau\tau} < 130$ GeV
  - $\text{BDT} > 0.34$

**TRAINED vs. $t\bar{t}$bar**
BDT training - $\tau_{\text{had}}\tau_{\text{lep}}$

- **BDT training input:**
  - 4-vectors of $\tau_1, \tau_2, b_1, b_2$
  - 4-vectors of $H_{\tau\tau}, H_{bb}, HH$
  - $E_{T}$\text{miss}$
  - MT2, $m_T(\tau_1), m_T(\tau_2), H_T$

- **Final Selection:**
  - $100 < m_{bb} < 130$ GeV
  - $80 < m_{\tau\tau}$ (MET corr.) < 130 GeV
  - BDT > 0.26

**TRAINED vs. Top pair**
## Systematics assumptions

<table>
<thead>
<tr>
<th></th>
<th>Very aggressive (I)</th>
<th>Aggressive (II)</th>
<th>Conservative (III)</th>
</tr>
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<tbody>
<tr>
<td><strong>Tau ID</strong></td>
<td>1 %</td>
<td>2,5 %</td>
<td>5 %</td>
</tr>
<tr>
<td><strong>b-jet ID</strong></td>
<td>0,25 %</td>
<td>0,5 %</td>
<td>1 %</td>
</tr>
<tr>
<td><strong>ele ID</strong></td>
<td>0,25 %</td>
<td>0,5 %</td>
<td>1 %</td>
</tr>
<tr>
<td><strong>mu ID</strong></td>
<td>0,1 %</td>
<td>0,25 %</td>
<td>0,5 %</td>
</tr>
<tr>
<td><strong>ttbar norm.</strong></td>
<td>1 %</td>
<td>1 %</td>
<td>1 %</td>
</tr>
<tr>
<td><strong>single H norm.</strong></td>
<td>1 %</td>
<td>1 %</td>
<td>1 %</td>
</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>1 %</td>
<td>1 %</td>
<td>1 %</td>
</tr>
</tbody>
</table>
Expected sensitivity: $bb\tau_{had}\tau_{had}$

varying uncertainties:

- $\delta k_\lambda (\text{stat}) \approx 3\%$
- $\delta k_\lambda (\text{stat + syst}) \approx 5-10\%$

varying (0.5x-5x) background yields:

- $\delta k_\lambda \approx 5-15\%$

always assuming SC.III

assuming SC.III $\rightarrow$ SC.I

$p_T > 60$ GeV
Expected sensitivity: $bb\tau_{\text{had}}\tau_{\text{lep}}$

- **FCC-hh Simulation (Delphes)**
  - $\sqrt{s} = 100$ TeV
  - $L = 30$ ab$^{-1}$
  - $HH \rightarrow bb\tau_{\text{had}}\tau_{\text{had}}$

**Varying uncertainties:**

| $\delta k_\lambda (\text{stat})$ | $\approx 6\%$ |
| $\delta k_\lambda (\text{stat + syst})$ | $\approx 10-12\%$ |

**Background yields:**

| $\delta k_\lambda$ | $\approx 6-16\%$ |

always assuming SC.III

assuming SC.III $\rightarrow$ SC. I

$p_T > 60$ GeV
Combination $bb\tau\tau$

Fully hadronic versus semi-leptonic

FCC-hh Simulation (Delphes)

$\sqrt{s} = 100$ TeV

$L = 30$ ab$^{-1}$

$HH \rightarrow bb\tau\tau$

$varying

uncertainties:$

$\delta k_\lambda (stat) \approx 4\%$

$\delta k_\lambda (stat + syst) \approx 5-12\%$
Combination of all channels

\[ \lambda_{\text{obs}} / \lambda_{\text{SM}} = k_\lambda \]

\[ \ln L = -2 \Delta \]

\( \sqrt{s} = 100 \text{ TeV} \)

\( L = 30 \text{ ab}^{-1} \)

Most aggressive systematic scenario for bbTT
Conclusions & outlook

• FCC-ee can measure in single Higgs production:
  
  • $\delta_{K\lambda}(\text{stat}) \approx 35\% \ (21\%)$ with 2 IPs (4 IPs)

• FCC-hh can reach $\delta_{K\lambda}(\text{stat}) \approx 5\%$ using double Higgs production, via:
  
  • $b\bar{b}\gamma\gamma$: $\delta_{K\lambda} \approx 5\%-7\%$
  • $b\bar{b}t\bar{t}$: $\delta_{K\lambda} \approx 5\%-10\%$ (using $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$)
  • $b\bar{b}4l$: $\delta_{K\lambda} \approx 10\%-20\%$
  • $b\bar{b}bb$: $\delta_{K\lambda} \approx 20\%-30\%$
  • $b\bar{b}WW$: $\delta_{K\lambda} \approx 40\%$
BACKUP
Baseline

- Detailed analysis performed in 2016 (summarised in the Yellow Report [1606.09408])
  - cut-based analysis
  - reported sensitivity on $\lambda$ after 30 ab$^{-1}$ at 100 TeV
  - studied impact of **detector performance**, systematics, background normalisation

![precision on $\lambda$ vs diphoton mass window: $m_{\gamma\gamma} = m_{m_1} - \Delta m_1 (B = 30.0 \text{ ab}^{-1})$](image)

<table>
<thead>
<tr>
<th>$\Delta S$</th>
<th>$r_B = 0.5$</th>
<th>$r_B = 1.0$</th>
<th>$r_B = 1.5$</th>
<th>$r_B = 2.0$</th>
<th>$r_B = 3.0$</th>
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<tbody>
<tr>
<td>$\Delta S = 0.00$</td>
<td>2.7%</td>
<td>3.4%</td>
<td>4.1%</td>
<td>4.9%</td>
<td>5.8%</td>
</tr>
<tr>
<td>$\Delta S = 0.01$</td>
<td>3.4%</td>
<td>3.9%</td>
<td>4.6%</td>
<td>5.3%</td>
<td>6.1%</td>
</tr>
<tr>
<td>$\Delta S = 0.015$</td>
<td>3.9%</td>
<td>4.4%</td>
<td>5.0%</td>
<td>5.7%</td>
<td>6.4%</td>
</tr>
<tr>
<td>$\Delta S = 0.02$</td>
<td>4.4%</td>
<td>4.8%</td>
<td>5.4%</td>
<td>6.0%</td>
<td>6.8%</td>
</tr>
<tr>
<td>$\Delta S = 0.025$</td>
<td>5.2%</td>
<td>5.6%</td>
<td>6.0%</td>
<td>6.6%</td>
<td>7.3%</td>
</tr>
</tbody>
</table>

**UPDATES:**

- up-to-date **parton shower/underlying event modelling** (Pythia8 vs Pythia6)
- more recent FCC-hh **detector** description (4T vs 6T, smaller detector size)
- QCD background generation using 5f scheme ($jj\gamma, jj\gamma\gamma$)
- Up-to-date k-factors for backgrounds (ttH) and signal ($\lambda$-dependent)
The relevant lagrangian terms of $gg \rightarrow HH$ production in D=6 EFT

$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v} \left(1 - \frac{3}{2} c_H + c_6 \right) h^3 + \frac{\alpha_s c_g}{4\pi} \left( \frac{h}{v} + \frac{h^2}{2v^2} \right) G^a_{\mu\nu} G^{a\mu\nu}$$

$$- \left[ \frac{m_t}{v} \left(1 - \frac{c_H}{2} + c_t \right) \bar{t}_L t_R h + \text{h.c.} \right] - \left[ \frac{m_t}{v^2} \left( \frac{3c_t}{2} - \frac{c_H}{2} \right) \bar{t}_L t_R h^2 + \text{h.c.} \right]$$

arXiv:1410.3471

SM diagrams

ttHH non-linear interaction

Higgs-gluon contact interactions
The non-resonant double Higgs production allows to directly probe the Higgs trilinear coupling ($\lambda_{hhh}$). Even if in Run2 we do not have full sensitivity to “measure” SM $\lambda_{hhh}$

$\sigma^{\text{SM}}_{hh}(13\text{TeV}) = 33.45\text{fb}^{+4.3\%}_{-6.0\%}(\text{scale unc.}) \pm 3.1\%(\text{PDF+}\alpha_s \text{ unc})$\textsuperscript{[1]}

→ The BSM physics can be modelled in EFT adding dim-6 operators\textsuperscript{[2]} to the SM Lagrangian, and the physics can be described with 5 parameters: $\lambda_{hhh}$, $y_t$, $c_2$, $c_{2g}$, $c_g$

- Non SM top Yukawa and $\lambda_{hhh}$ couplings
- New diagrams and couplings in the game

To be noted:

in a linear EFT $c_g = c_{2g}$ and $c_2 = -(3m_t/2v)y_t$

\textsuperscript{[1]} LHCHXSWG Yellow Report 4
\textsuperscript{[2]} Phys. Rev. D\textbf{91} (2015), no. 11, 115008