Higgs self-coupling @100 TeV

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


**HH@ FCC-hh: production**

- negative interference between box and triangle
- high $m_{hh}$ region suppressed by off-shell propagator in triangle (and dominated by box)

\[ \frac{\sigma(100 \text{ TeV})}{\sigma(14 \text{ TeV})} \approx 40 \]

$\sigma$ (Gluon fusion):

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→ sensitivity to the self-coupling is determined by low $m_{hh}$ region
**HH@ FCC-hh: production and decay**

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

- Total rate still taken to be given by NNLL+NNLO in EFT (although known to be overshooting by 20%), but missing the following (should compensate?):
  - higher orders other channel ($N^nLO, n>2$)
  - VBF-HH/$ttHH$
bbyy
Selection

Acceptance cuts

\begin{itemize}
  \item $\gamma$ isolation $R = 0.4$
  \item $p_T(\text{had})/p_T(\gamma) < 0.15$
  \item jets: anti-$k_T$, parameter $R = 0.4$
  \item $|\eta_{b,\gamma,j}| < 6$
  \item $p_T(b), p_T(\gamma), p_T(j) > 35$ GeV
\end{itemize}

$m_{bb} \in [60, 200]$ GeV

$m_{\gamma \gamma} \in [100, 150]$ GeV

Backgrounds

- ttH
- jj$\gamma \gamma$
- jjj$\gamma$ (fake photons, fake b’s)

\[ p_j \rightarrow \gamma = \alpha \exp\left(-p_T,j/\beta\right) \]

Final selection

\begin{itemize}
  \item $\gamma$ isolation $R = 0.4$
  \item $(p_T(\text{had})/p_T(\gamma) < 0.15)$
  \item jets: anti-$k_T$, parameter $R = 0.4$
  \item $|\eta_{b,\gamma,j}| < 4.5$
  \item $p_T(b_1), p_T(\gamma_1) > 60$ GeV
  \item $p_T(b_2), p_T(\gamma_2) > 35$ GeV
  \item $m_{bb} \in [100, 150]$ GeV
  \item $p_T(bb), p_T(\gamma \gamma) > 100$ GeV
  \item $\Delta R(bb), \Delta R(\gamma \gamma) < 2.5, 3.0$
  \item no isolated leptons with $p_T > 25$ GeV
\end{itemize}
2D shapes

- exploit correlations of means in the signal, ex: $m_{\gamma\gamma}$ vs $m_{hh}$
- build parametric model in 2D $\rightarrow m_{\gamma\gamma}$: gauss, $m_{hh}$: landau+exp
- perform 2D Likelihood fit on the signal strength and coupling modifier:

$$\mu = \sigma_{\text{obs}}/\sigma_{\text{SM}} \quad \kappa_\lambda = \lambda_{\text{obs}}/\lambda_{\text{SM}}$$

FCC-hh Simulation (Delphes) $= 100$ TeV $s^{-1}$
$L = 30$ ab
Precision on the self-coupling

assuming QCD can be measured from sidebands

nominal background yields:

\[ \delta k_\lambda \text{(stat)} \approx 3.5\% \]
\[ \delta k_\lambda \text{(stat + syst)} \approx 4.5\% \]
\[ \delta r \text{(stat)} \approx 2.5\% \]
\[ \delta r \text{(stat + syst)} \approx 3\% \]

varying (0.5x-2x) background yields:

\[ \delta k_\lambda \text{(stat)} \approx 3 - 5\% \]
\[ \delta r \text{(stat)} \approx 2 - 3\% \]
Varying detector specifications

- Model tunable to include various effects/conditions on the objects
- Even with non-ideal configurations, 5% precision on $k\lambda$ seems to be within reach
4b - boosted
Approach

- \( \sigma(p p \rightarrow hhj, 100 \text{ TeV}) \approx 100 \times \sigma(p p \rightarrow hhj, 14 \text{ TeV}) \), with \( p_T(j) > 100 \text{ GeV} \)

- Exploit large branching ratio \( \text{BR}(H \rightarrow bb)^2 \approx 0.3 \)

- Requiring a boosted HH system recoiling against jet(s), contains the invariant mass to small values → maintain sensitivity to the self-coupling

- In practice low mass region \( m_{HH} \approx 200 \text{ GeV} \) is unresolvable:

\[
m_{HH} \approx p_T \times 2R_{jet} \quad \text{and} \quad R_{jet} \approx 2m_H/p_T \quad \Rightarrow \quad m_{HH} \approx 3-4 m_H
\]
Signal and backgrounds

Backgrounds

- QCD: (double gluon to b-bar splitting recoiling against jet)
  \[ p\ p \rightarrow 4b + j \text{ (or simply } p\ p \rightarrow j\ g\ g) \]
  \[ \sigma_{4b+j} (pT(j) > 500 \text{ GeV}) \sim 57 \text{ fb} \ (10^9 @ 30\text{ab}^{-1}) \]

- \( \text{ttbar, ZH} \ldots \)

Signal

- \( pp \rightarrow hh + j \)
  \[ \sigma_{hh+j} (pT(j) > 500 \text{ GeV}) \sim 4 \text{ fb} \ (10^5 @ 30\text{ab}^{-1}) \]

If aim for % level precision, need S,B \( \approx 10^4 \) after cuts:
  i.e. a factor of \( 10^5 \) in background rejection \( \rightarrow \) very hard!!
  \( \rightarrow \) explore lower \( p_T(hh) \) range as well ….
Selection strategy

- Boost the di-Higgs system:
  - $p_T(h_1 h_2) > 250$ GeV
- Preselection: Require $\gtrsim 2$ b-tagged fatjets $R = 0.8$
  - $p_T(h_1) > 400$ GeV and $|\eta_1| < 3.0$
  - $p_T(h_2) > 300$ GeV and $|\eta_2| < 3.0$
- Higgs tagging:
  - $100 < m_{SD}(h_1) < 135$ and $\tau_{2,i}^{[1]}(h_1) < 0.4$
  - $100 < m_{SD}(h_2) < 135$ and $\tau_{2,1}(h_2) < 0.4$

$\Rightarrow$ fit the $m_{HH}$ spectrum

Expected sensitivity

varying (0.5x-2x) background yields:

\[ \delta \mu \text{ (stat)} \approx 10 - 20 \% \]

\[ \delta \kappa \lambda \text{ (stat)} \approx 20 - 40 \% \]
bbττ -boosted

[1802.01607]
Approach

- $\sigma(pp \rightarrow hhj, 100 \text{ TeV}) \approx 100 \times \sigma(pp \rightarrow hhj, 14 \text{ TeV})$, with $p_T(j) > 100 \text{ GeV}$

- Exploit large branching ratio $2 \times \text{BR}(H \rightarrow bb) \times \text{BR}(H \rightarrow \tau \tau) \approx 7\%$

- Requiring a boosted HH system recoiling against jet(s), contains the invariant mass to small values $\rightarrow$ maintain sensitivity to the self-coupling

- Final states: both $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{lep}}\tau_{\text{lep}}$ considered, but $\tau_{\text{lep}}\tau_{\text{had}}$ by far the best…

- Resolved analysis and $\tau_{\text{had}}\tau_{\text{had}}$ final state were not considered, but they are by far the most sensitive ones at LHC-PhaseII and in HL-LHC simulations

Backgrounds:

- $t\bar{t}+\text{jets}$
- $Z_{\text{bb}} + \text{jets (EWK + QCD)}$
- $ZZ/ZH$ (EWK)
- $W+\text{jets (neglected)}$

Caveat: no detector simulation!
Analysis strategy

- 1 Higgs tagged jet, with double-b tag, $p_T > 150$ GeV
- $\tau_{\text{had}}$ tagged
- lepton $p_T > 20$ GeV
- BDT based analysis

\[
\delta \kappa_{\lambda} (\text{stat}) \approx 8 \%
\]
bb4l
Analysis strategy

- H → 4 leptons + 2b’s (for now only muons)

Backgrounds:
- $ttH, H \rightarrow 4$ leptons
- 4l + jets ($ZZ^*, Z^*Z^*, ZZ$) continuum (neglected for now)
- $pp \rightarrow H b b \rightarrow 4l bb$

Method:
- reconstruct Higgs peak
- $120 < M_{4\mu} < 130; 80 < M_{bb} < 130$
- additional handle for $ttH \rightarrow \Delta R(b,b)$
Precision on the signal strength

\[ \delta r(\text{stat}) \approx 10 - 15\% \]

\[ \delta \kappa(\text{stat}) \approx 20 - 30\% \]
bbWW → bblvqq

- 80 < mbb < 150 GeV
- p_T(WW) > 150 GeV

Backgrounds:
- bbWW
- V+jets

\[ \delta r(\text{stat}) \approx 20\% \]
\[ \delta k_\lambda(\text{stat}) \approx 40\% \]
Conclusions & outlook

- **HH→bbγγ** analysis has been performed with more recent detector description and new MC samples
  - small differences have been observed but overall comparable performance on sensitivity
    \[ \delta \kappa_{\lambda}(\text{stat}) \approx 3.5\% \]

- **HH recoil** displays lower performance due to huge QCD background
  - **bbbbj:** sensitivity \[ \delta \kappa_{\lambda}(\text{stat}) \approx 20-30\% \]
  - **bbττj:** sensitivity found \[ \delta \kappa_{\lambda}(\text{stat}) \approx 10\% \] (using only \(\tau_{\text{lep}}\tau_{\text{had}}\))

- **HH → 4lbb** (preliminary)
  - looks very promising with \[ \delta \kappa_{\lambda}(\text{stat}) \approx 20-30\% \]

- **HH→bbWW→lνbbjj**
  - \[ \delta \kappa_{\lambda}(\text{stat}) \approx 40\% \]
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

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<th>$\Delta S = 0.01$</th>
<th>$\Delta S = 0.015$</th>
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**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)
Precision on the signal strength

assuming QCD can be measured from sidebands

nominal background yields:

\[ \frac{\sigma_{\text{obs}}}{\sigma_{\text{SM}}} = 0.92, 0.94, 0.96, 0.98, 1, 1.02, 1.04, 1.06, 1.08 \]

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

\[ -2 \Delta L = 0, 2, 4, 6, 8, 10, 12, 14, 16 \]

\[ \delta r_{\text{stat}} \approx 2.5\% \]

\[ \delta r_{\text{stat + syst}} \approx 3\% \]

varying (0.5x-2x) background yields:

\[ \frac{\sigma_{\text{obs}}}{\sigma_{\text{SM}}} = 1, 1.02, 1.04, 1.06, 1.08 \]

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

\[ -2 \Delta L = 0, 2, 4, 6, 8, 10, 12, 14, 16 \]

\[ \delta r_{\text{stat + syst}} \approx 2 - 3\% \]
2D scan

\[ \frac{\sigma_{\text{obs}}}{\sigma_{\text{SM}}} = \frac{1}{k} \]

\[ \alpha_{\text{SM}} \]

\[ \sqrt{s} = 100 \text{ TeV} \]

\[ L = 30 \text{ ab}^{-1} \]

\[ h^2d \]

Entries: 10000

Mean x: 0.6962

Mean y: 0.5595

Std Dev x: 0.4483

Std Dev y: 0.5243

FCC-hh Simulation (Delphes)
The relevant lagrangian terms of $gg\rightarrow HH$ production in D=6 EFT

$$
\mathcal{L}_{hh} = -\frac{m_h^2}{2v} \left( 1 - \frac{3}{2} c_H + c_6 \right) h^3 + \frac{\alpha_s c_g}{4\pi} \left( \frac{h}{v} + \frac{h^2}{2v^2} \right) G_{\mu\nu}^a G_{\mu\nu}^a 
- \left[ \frac{m_t}{v} \left( 1 - \frac{c_H}{2} + c_t \right) \bar{t}L tR h \right] + \text{h.c.} 
- \left[ \frac{m_t}{v^2} \left( \frac{3c_t - c_H}{2} \right) \bar{t}L tR h^2 \right] + \text{h.c.}
$$

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 $\lambda_{hhh}$

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

$\rightarrow$ The BSM physics can be modelled in EFT adding dim-6 operators[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 $c_2 = -(3m_t/2v) y_t$

[1] LHCHXSWG Yellow Report 4