Higgs measurements and perspectives at the FCC-hh

Michele Selvaggi
CERN

For an overview of Higgs studies and links to existing documents, see:

A framework and goals for FCC-hh physics studies at Snowmass 2021, C.Helsens, M.Mangano, MS
http://cds.cern.ch/record/2717892

Also:
- Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies, Contino et al, [1606.09408]
- Measuring the Higgs self-coupling via Higgs-pair production at a 100 TeV p-p collider, MLM, Ortona, MS [2004.03505]
The FCC project

Within the FCC collaboration (CERN as host lab), 5 main accelerator facilities have been studied:

- **pp-collider (FCC-hh)**
  - defines infrastructure requirements
  - $16 \, \text{T} \rightarrow 100 \, \text{TeV}$ in 100 km tunnel

- **ee-collider (FCC-ee):**
  - as a (potential) first step

- **ep collider (FCC-eh)**

- **HE-LHC :**
  - $27 \, \text{TeV}$ ($16\, \text{T}$ magnets in LHC tunnel)

- **Low E FCC-hh**
  - $100 \, \text{km} - 6\, \text{T} - 37 \, \text{TeV}$

CDRs and European Strategy documents have been made public in Jan. 2019

[https://fcc-cdr.web.cern.ch/](https://fcc-cdr.web.cern.ch/)
Why measuring Higgs @FCC-hh

• 100 TeV provides unique and complementary measurements to e+e- colliders:
  
  • Higgs self-coupling
  • top Yukawa
  • Higgs → invisible
  • rare decays (BR(\(\mu\mu\)), BR(\(Z\gamma\)), ratios, ..) measurements will be statistically limited at FCC-ee

- Assuming, we know production xsec and luminosity, at pp colliders we measure \(BR(i) = \Gamma_i / \Gamma_H\)

- By performing measurements of ratios of couplings, (or BRs), FCC-ee allows to “convert” relative measurements into absolute via HZZ

\[
\text{BR}(H \rightarrow XX) / \text{BR}(H \rightarrow ZZ) \approx \frac{g_X^2}{g_Z^2}
\]

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\delta \Gamma_H / \Gamma_H \text{ (%)})</td>
<td>SM</td>
<td>1.3</td>
</tr>
<tr>
<td>(\delta g_{HZZ} / g_{HZZ} \text{ (%)})</td>
<td>1.5</td>
<td>0.17</td>
</tr>
<tr>
<td>(\delta g_{HWW} / g_{HWW} \text{ (%)})</td>
<td>1.7</td>
<td>0.43</td>
</tr>
<tr>
<td>(\delta g_{Hbb} / g_{Hbb} \text{ (%)})</td>
<td>3.7</td>
<td>0.61</td>
</tr>
<tr>
<td>(\delta g_{Hcc} / g_{Hcc} \text{ (%)})</td>
<td>\text{~}70</td>
<td>1.21</td>
</tr>
<tr>
<td>(\delta g_{Hgg} / g_{Hgg} \text{ (%)})</td>
<td>2.5 (gg→H)</td>
<td>1.01</td>
</tr>
<tr>
<td>(\delta g_{Htt} / g_{Htt} \text{ (%)})</td>
<td>1.9</td>
<td>0.74</td>
</tr>
<tr>
<td>(\delta g_{H\mu\mu} / g_{H\mu\mu} \text{ (%)})</td>
<td>4.3</td>
<td>9.0</td>
</tr>
<tr>
<td>(\delta g_{HYY} / g_{HYY} \text{ (%)})</td>
<td>1.8</td>
<td>3.9</td>
</tr>
<tr>
<td>(\delta g_{Htt} / g_{Htt} \text{ (%)})</td>
<td>3.4</td>
<td>–</td>
</tr>
<tr>
<td>(\delta g_{HZZ} / g_{HZZ} \text{ (%)})</td>
<td>9.8</td>
<td>–</td>
</tr>
<tr>
<td>(\delta g_{H\mu\mu} / g_{H\mu\mu} \text{ (%)})</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>

\(BR_{\text{exo}} \text{ (95\%CL)}\) \(\text{BR}_{\text{inv}} < 2.5\%\) \(< 1\%\)
Why Higgs at FCC-hh?

- Large Higgs production rates (x20-60 cross-section wrt to LHC):
  - access (very) rare decay modes (e.g. 2nd gen.), complementary to ee colliders
  - push to %-level Higgs self-coupling measurement

- Large dynamic range for H production (in $p_T^H$, $m(H+X)$, …):
  - new opportunities for reduction of syst. uncertainties (TH and EXP)
  - develop indirect sensitivity to BSM effects at large $Q^2$, complementary to that emerging from precision studies (e.g. decay BRs) at $Q \sim m_H$

- High energy reach:
  - direct probes of BSM extensions of Higgs sector (e.g. SUSY)
  - Higgs decays of heavy resonances
  - Higgs probes of the nature of EW phase transition (strong 1st order? crossover?)
Higgs at large $p_T @ 100$ TeV

- Huge rates at large $p_T$:
  - $> 10^6$ Higgs produced with $p_T > 1$ TeV
  - Higher probability to produce large $p_T$ Higgs from ttH/VBF/VH at large
  - Even rare decay modes can be accessed at large $p_T$

- Opportunity to measure the Higgs in a new dynamical regime
  - Higgs $p_T$ spectrum highly sensitive to new physics.

To do:

assess TH systematics for Higgs production at large $p_T$ and how impacts sensitivity
Top Yukawa (production)

- production ratio $\sigma(ttH)/\sigma(ttZ) \approx y_t^2 y_b^2/ g_{ttZ}^2$
- measure $\sigma(ttH)/\sigma(ttZ)$ in $H/Z \rightarrow bb$ mode in the boosted regime, in the semi-leptonic channel
- perform simultaneous fit of double $Z$ and $H$ peak
- (lumi, scales, pdfs, efficiency) uncertainties cancel out in ratio

- assuming $g_{ttZ}$ and $\kappa_b$ known to 1% (from FCC-ee),
  $\rightarrow$ measure $y_t$ to 1%

To do:

- Further assess systematics related to $ttbb$ background modelling
- Explore use $ttH / ttZ$ in $tt\tau\tau$ decay mode
Higgs decays (rare)

- study sensitivity as a function of minimum $p_T(H)$ requirement in the $\gamma\gamma$, ZZ(4l), $\mu\mu$ and $Z(ll)\gamma$ channels
- low $p_T(H)$: large statistics and high syst. unc.
- large $p_T(H)$: small statistics and small syst. unc.
- $O(1-2\%)$ precision on BR achievable up to very high $p_T$ (means 0.5-1% on the couplings)

- measure ratios of BRs to cancel correlated sources of systematics:
  - luminosity
  - object efficiencies
  - production cross-section (theory)

To do:

- Exploit specific signatures of various production modes (categorize)
Higgs decays

To do:

- Following the principle of reducing as much as possible the impact of systematics assumptions on future measurements, additional ratio measurements:

\[
\frac{\sigma(WH[\rightarrow \gamma\gamma])}{\sigma(WZ[\rightarrow e^+e^-])} \rightarrow G_W = g_{HWW}^2 \times BR(H \rightarrow \gamma\gamma)
\]

\[
\frac{\sigma(WH[\rightarrow \tau\tau])}{\sigma(WZ[\rightarrow \tau\tau])} \rightarrow G_\tau = g_{HWW}^2 \times BR(H \rightarrow \tau\tau)
\]

\[
\frac{\sigma(WH[\rightarrow bb])}{\sigma(WZ[\rightarrow bb])} \rightarrow G_b = g_{HWW}^2 \times BR(H \rightarrow bb)
\]

Also:

\[
\frac{\sigma(Z[\nu\nu]H[\rightarrow \gamma\gamma])}{\sigma(Z[\nu\nu]Z[\rightarrow e^+e^-])}
\]

\[\delta G/G < 1\%
\]

- Boosted Higgs studies:
  - in hadronic channels (H\rightarrow bb/cc/WW)
  - exclusive decays H\rightarrow (J/\psi) \rho / \omega / \chi (resolved/boosted)
Higgs self-coupling

- Very small cross-section due to negative interference with box diagram
- HL-LHC projections: $\delta k_\lambda / k_\lambda \approx 50\%$
- Expect large improvement at FCC-hh:
  - $\sigma(100\text{ TeV})/\sigma(14\text{ TeV}) \approx 40$ (and $L \times 10$)
  - $x400$ in event yields and $x20$ in precision
- main channels studied (using MVA):
  - $bb\gamma\gamma$ ($\delta k_\lambda / k_\lambda \sim 3\%-8\%$)
  - $bb\tau\tau$ ($\delta k_\lambda / k_\lambda \sim 12\%$)
  - $bbZZ(4l)$ ($\delta k_\lambda / k_\lambda \sim 15\%$)
  - $bbbb$ ($\delta k_\lambda / k_\lambda \sim 22\%$)
Higgs self-coupling (combination)

δk_λ / k_λ \sim 3.0 - 5.5\% assuming SM couplings

To do:

- Exploit other channels — both production and decay (e.g. γγWW, 4b boosted)
- Improve assessment of impact of detector effects on the final sensitivity in order to define target for detector design
  - e.g. pile-up and timing resolution
- Study in the context of a global EFT fit (here \kappa_λ fit)
$W_L W_L \rightarrow HH$

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

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, $\delta c_{2V} < 1$

To do:

- Explore including detector effects and state-of-the-art boosted techniques
- Extend to low mass and study impact on $kl$ (interplay with ggHH(4b) analysis — both resolved and boosted)
- Assess impact in a global EFT fit interpretation
Conclusions & outlook

• **Large statistics** ($10^{10}$ Higgs bosons) open up a whole new range of possibilities, allowing for precision in new kinematic regimes, and rare decay channels $\rightarrow$ complementary to FCC-ee

• Measuring **ratios of couplings** (or equivalently BRs), allows to cancel systematics (1% precision on “rare” couplings within reach after absolute HZZ measurement in e+e-)

• Higgs-self coupling can be measured with $\delta k_{\lambda} \approx 3$-$5\%$ precision at FCC-hh (best achievable precision among all future facilities)

• Can directly and indirectly exclude compelling classes of models compatible with 1st order electroweak phase transition

• Many more interesting studies to be done, not discussed in this talk:
  
  • gauge boson pair production at large mass (to study anomalous couplings)
  • differential measurements: Higgs $p_T$ in the multi-TeV, as a probe of BSM physics

• To get started see instructions here (and feel free to contact us):

  A framework and goals for FCC-hh physics studies at Snowmass 2021

  http://cds.cern.ch/record/2717892
Backup