Higgs & EWSB @FCC-hh

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ICHEP 2018 - Seoul
The FCC-hh

- 100 km pp collider
- $E_{CM} = 100$ TeV
- 16T magnets

Access to:

- direct searches:
  - heavy $Z'$ reach up to $m \approx 40$ TeV
  - stops up to $m \approx 15$ TeV

- precision SM measurements:
  - Higgs potential, self-coupling
  - Higgs, Top, EWK physics in new dynamical regimes (complementary to $e^+e^-$)
Why measuring Higgs \(\text{@FCC-hh}\)?

**HL-LHC**

- Higgs precision measurements are guaranteed deliverables

- FCC-hh provides unique and complementary measurements to e\(^+\)e\(^-\) colliders:
  - Higgs self-coupling
  - top Yukawa
  - rare decays (\(\text{BR}(\mu\mu), \text{BR}(Z\gamma), \) ratios, ..) measurements will be statistically limited at FCC-ee

- Directly test unitarisation of VBS by measuring \(W_LW_L\) and \(Z_LZ_L\) (barely observable @HL-LHC)

**FCC-ee**

<table>
<thead>
<tr>
<th>(\delta m_H) (MeV)</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\delta \Gamma_H / \Gamma_H) (%)</td>
<td>1.6</td>
</tr>
<tr>
<td>(\delta g_{Hb} / g_{Hb}) (%)</td>
<td>0.68</td>
</tr>
<tr>
<td>(\delta g_{HW} / g_{HW}) (%)</td>
<td>0.47</td>
</tr>
<tr>
<td>(\delta g_{H\ell} / g_{H\ell}) (%)</td>
<td>0.80</td>
</tr>
<tr>
<td>(\delta g_{H\gamma} / g_{H\gamma}) (%)</td>
<td>3.8</td>
</tr>
<tr>
<td>(\delta g_{H\mu} / g_{H\mu}) (%)</td>
<td>8.6</td>
</tr>
<tr>
<td>(\delta g_{HZ} / g_{HZ}) (%)</td>
<td>0.22</td>
</tr>
<tr>
<td>(\delta g_{Hc} / g_{Hc}) (%)</td>
<td>1.2</td>
</tr>
<tr>
<td>(\delta g_{Hg} / g_{Hg}) (%)</td>
<td>1.0</td>
</tr>
<tr>
<td>(\text{Br}_{\text{inv}} %(\text{95%CL}))</td>
<td>&lt; 0.25</td>
</tr>
<tr>
<td>(\text{BR}_{\text{EXG}} %(\text{95%CL}))</td>
<td>&lt; 1.1</td>
</tr>
</tbody>
</table>
Higgs self-coupling at FCC-hh

- Very small cross-section due to **negative interference** with box diagram
- HL-LHC projections: $\delta \lambda / \lambda = 100%$
- 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
- mainly 4 channels studied:
  - $bb\gamma\gamma$ (most sensitive)
  - $bbZZ(4l)$
  - $bbbbj$ (boosted)
  - $bbWW$
**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 \(k_λ\)
  - \(δk_λ/k_λ = 5\%\) achievable
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)
- $\delta k_\lambda / k_\lambda = 15$-20% depending on systematics assumptions
**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 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

$$\Delta R \approx 2m_H / p_T$$
Higgs measurements @FCC-hh

<table>
<thead>
<tr>
<th></th>
<th>σ(13 TeV)</th>
<th>σ(100 TeV)</th>
<th>(\sigma(100)/\sigma(13))</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH (N³LO)</td>
<td>49 pb</td>
<td>803 pb</td>
<td>16</td>
</tr>
<tr>
<td>VBF (N³LO)</td>
<td>3.8 pb</td>
<td>69 pb</td>
<td>16</td>
</tr>
<tr>
<td>VH (N³LO)</td>
<td>2.3 pb</td>
<td>27 pb</td>
<td>11</td>
</tr>
<tr>
<td>ttH (N³LO)</td>
<td>0.5 pb</td>
<td>34 pb</td>
<td>55</td>
</tr>
</tbody>
</table>

**Expected improvement at FCC-hh:**

- 20 billion Higgses produced at FCC-hh
- factor 10-50 in cross sections (and Lx10)
- reduction of a factor 10-20 in statistical uncertainties

**Large statistics will allow:**

- for % - level precision in statistically limited rare channels (\(\mu\mu, Z\gamma\))
- in systematics limited channel, to isolate cleaner samples in regions (e.g. @large Higgs \(p_T\)) with:
  - higher S/B
  - smaller impact of systematics
Higgs decays

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

- measure ratios of BRs to cancel correlated sources of systematics:
  - luminosity
  - object efficiencies
  - production cross-section (theory)
- Becomes absolute precision measurement in particular if combined with $H \rightarrow ZZ$ measurement from $e^+e^-$ (at 0.1%)

- 1% lumi + theory uncertainty
- $p_T$ dependent object efficiency:
  - $\delta \varepsilon(e/\gamma) = 0.5\,(1)\% \text{ at } p_T \rightarrow \infty$
  - $\delta \varepsilon(\mu) = 0.25\,(0.5)\% \text{ at } p_T \rightarrow \infty$
Top Yukawa

- production ratio $\sigma(ttH)/\sigma(ttZ)$
- predicted to 1% precision [1507.08169]
- measure $\sigma(ttH)/\sigma(ttZ)$ in $H/Z \to bb$ mode in the boosted regime, in the semi-leptonic channel
- perform simultaneous fit of double $Z$ and $H$ peak

$\delta y_t / y_t \lesssim 1 \%$
Vector Boson Scattering

- First opportunity to measure precisely the $V_L V_L$ component that unitarizes VBS at high energy (barely $3\sigma$ at HL-LHC)
- Sets constraints on detector acceptance (fwd jets at $\eta \approx 4$)
- Study $W^+/-W^+/-$ (same-sign) channel
- Large $WZ$ background at FCC-hh
- 3-4% precision on $W_L W_L$ scattering achievable with full dataset!
Conclusions & outlook

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

• The FCC-hh machine will produce $> 10^{10}$ Higgs bosons

• Such large statistics open up a whole new range of possibilities, allowing for precision in new kinematic regimes

• 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-)

• VBS longitudinal polarisations $V_L V_L$ can be measured at 3-4% precision ($W_L W_L$ same sign)

• Extremely rich Higgs program at the FCC, that goes much beyond (light yukawa, Higgs off-shell width measurement, Higgs differentials) still to be studied …