Higgs and EWSB @ FCC-hh

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On behalf of the FCC-hh physics group

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Expectation from hadron future collider

Guaranteed deliverables
• Study Higgs and top-quark properties and exploration of EWSB phenomena with unmatchable precision and sensitivity

Exploration potential (New machines are build to make discoveries!)
• Mass reach enhanced by factor $\sqrt{s}/14\text{TeV}$ (5-7 at 100TeV)
  • Statistics enhanced by several orders of magnitude for possible BSM seen at HL-LHC
• Benefit from both direct (large $Q^2$) and indirect precision probes

Could provide firm answers to questions like
• Is the SM dynamics all there at the TeV scale?
• Is there a TeV-Scale solution the hierarchy problem?
• Is DM a thermal WIMPS?
• Was the cosmological EW phase transition 1$^{\text{st}}$ order? Cross-over?
• Could baryogenesis have taken place during EW phase transition?
The FCC-hh

FCC-hh

• Need a new 100km tunnel
• Need 16 Tesla magnet to reach 100TeV in 100km
• Baseline Luminosity (10y)
  • $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (HL-LHC) $<\mu>200$
• Ultimate luminosity (15y)
  • $30 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ $<\mu>1000$
• 2.4MW sync rad/ring x300 HL-LHC
• Considering 30 ab$^{-1}$ for the study
Environment and detector requirements

@100TeV FCC-hh

- pp cross-section from 14 to 100TeV only grows by a factor 2
- 10 times more fluence compared with HL-LHC (x100 wrt to LHC)
  - Need radiation hard detectors
- The radiation level increase mostly driven by the jump in instantaneous luminosity
- More forward physics -> larger acceptance
  - Precision momentum spectroscopy and energy measurements up to $|\eta|<4$
  - Tracking and calorimetry up to $|\eta|<6$ (at 10cm of beam line at 18m of IP)
- More energetic particles
  - colored hadronic resonances up to 40TeV -> Full containment of jets up to 20TeV
  - Resonances decaying to boosted objects (top, bosons) -> need very high granularity to resolve such sub-structure
Why measuring Higgs @FCC-hh?

- Higgs precision measurements are part of the guaranteed deliverables
- FCC-hh provides unique and complementary measurements to $e^+e^-$ colliders:
  - Higgs self-couplings
  - Top Yukawa
  - Rare decays (BR($\mu\mu$), BR($Z\gamma$), ratios, ...) measurements will be statistically limited at FCC-ee
Higgs self-coupling @ 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:
  - $\sigma(100\ TeV) / \sigma(14\ TeV) \approx 40$ (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 \rightarrow bb\gamma\gamma

- BR=0.25%, and large QCD backgrounds (jj\gamma\gamma and \gamma+jets)
- Main difference w.r.t LHC is the very large ttH background
- Strategy:
  - exploit correlation of means in (m_{\gamma\gamma}, m_{hh}) in signal
  - build a parametric model in 2D
  - perform a 2D Likelihood fit on the coupling modifier $k_\lambda$
  - $\delta k_\lambda / k_\lambda = 5\%$ achievable
HH → bb4l

- **New channel** opening at (cross-section 180ab) 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
- Key element for the detector design are powerful reconstruction of low energetic electrons and muons
**HH → 4b+j boosted**

- Large rate allow to look for boosted HH recoiling against a jet (low $m_{HH}$ drives the sensitivity)
- Relies on the 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
Higgs and EW phase transition

- Strong 1st order EWPT required to induce matter-antimatter asymmetry at EW scale
- Simple model: extension of the SM scalar sector with a single real singlet scalar
  - Contains 2 higgs scalar, $h_1$ and $h_2$
  - Interaction of scalar potential can lead to 1st EWPT when SM-like state $h_1$ has a mass of 125GeV
  - Modifications in Higgs self coupling, shift in $Z_h$, direct production of scalar pairs
- Parameter space scan for this simple model extension of the SM

![Graph showing $N_\sigma$ vs $m_2$](image)

$h_2 \rightarrow h_1 h_1 \rightarrow 4\tau/\gamma\gamma bb$

![Graph showing hZZ coupling vs hhh coupling](image)
Higgs measurements @ FCC-hh

- Expected improvements @ FCC-hh:
  - $2 \times 10^{10}$ Higgses produced
  - Factor 10-50 in cross sections (and $L \times 10$)
  - Reduction of a factor 10-20 in stat. unc.

- 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

<table>
<thead>
<tr>
<th></th>
<th>$\sigma(13$ TeV)</th>
<th>$\sigma(100$ TeV)</th>
<th>$\sigma(100)/\sigma(13)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggH$ (N$^3$LO)</td>
<td>49 pb</td>
<td>803 pb</td>
<td>16</td>
</tr>
<tr>
<td>$VBF$ (N$^2$LO)</td>
<td>3.8 pb</td>
<td>69 pb</td>
<td>16</td>
</tr>
<tr>
<td>$VH$ (N$^2$LO)</td>
<td>2.3 pb</td>
<td>27 pb</td>
<td>11</td>
</tr>
<tr>
<td>$t\bar{t}H$ (N$^3$LO)</td>
<td>0.5 pb</td>
<td>34 pb</td>
<td>55</td>
</tr>
</tbody>
</table>

Graph: $N = \sigma(p_{T,H}>p_{T,\text{min}}) \times 30$ $\text{ab}^{-1}$

- Solid: $gg\rightarrow H$
- Dashes: $t\bar{t}H$
- Short dash: VBF
- Dotdash: WH
Higgs as a probe for BSM: precision/reach

\[ \mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{C_i}{\Lambda^2} O_i + \ldots \]

\[ O = |\langle f | L | i \rangle|^2 = O_{SM} \left[ 1 + O(\mu^2/\Lambda^2) + \ldots \right] \]

- For H decays, or inclusive production, \( \mu \sim O(v,m_H) \)
  
  \[ \delta O \sim \left( \frac{v}{\Lambda} \right)^2 \sim 6\% \left( \frac{\text{TeV}}{\Lambda} \right)^2 \]

- Precision probes large \( \Lambda \) e.g. \( \delta O=1\% \Rightarrow \Lambda \sim 2.5 \text{ TeV} \)

- For H production off-shell or with large momentum transfer \( Q \), \( \mu \sim O(Q) \)
  
  \[ \delta O \sim \left( \frac{Q}{\Lambda} \right)^2 \]

- Kinematic reach probes large \( \Lambda \) even if precision is “low” e.g. \( \delta O=10\% \) at \( Q=1.5 \text{ TeV} \Rightarrow \Lambda \sim 5 \text{ TeV} \)

Complementarity between super-precise measurements at ee collider and large-Q studies at 100 TeV
Di-higgs in VBS

\[ A(V_L V_L \rightarrow HH) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_{V}^2) + O(m_W^2/\hat{s}) \]

- Considering the 4b boosted final state
- \( c_V \) measured at per mille a FCC-ee

In the SM, \( c_{2V} = c_V^2 \)

arXiv:1611.03860
Conclusion and 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 as well as very strong probe for BSM
- Measuring ratios of couplings (or equivalently BRs), allows to cancel systematics (1% precision on “rare” couplings within reach after absolute HZZ measurement in $e^+e^-$)
- Extremely rich Higgs program at the FCC, that goes much beyond (light yukawa, Higgs off-shell width measurement, Higgs differentials) still to be studied ...
- FCC CDRs for sign-up [https://indico.cern.ch/event/750953/](https://indico.cern.ch/event/750953/)
- Soon printed and published
HEP Landscape

- Particle accelerators are built to answer some of the most fundamental questions about the natural world
- Physics priorities are likely to shift swiftly, as we advance in our exploration, both experimentally and theoretically
- There are many unknowns ahead of us that may reshuffle the cards (e.g. any discoveries of HL-LHC)

→ We need a broad and bold program capable of adapting to the swift changes in the physics landscape that are likely to happen
→ 100TeV hadron collider – In times of uncertainty, bold exploration is the way to go

Complementarity and synergy with high-luminosity lepton machine, FCC-ee
A 100km circular collider as “natural” next the step

27km tunnel

The next step: 100km tunnel

The FCC design study is establishing the feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology

Both FCC-ee and FCC-hh have outstanding physics cases

We are ready to move to the next step, as soon as possible
Additional material
Deviations in the Higgs $p_T$ spectrum

Top-partners in The loop

$10^6$ at 100 TeV!

arXiv:1308.4771

<table>
<thead>
<tr>
<th>Point</th>
<th>$m_{\tilde{t}}$ [GeV]</th>
<th>$m_{\tilde{b}}$ [GeV]</th>
<th>$A_t$ [GeV]</th>
<th>$\Delta$</th>
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</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>171</td>
<td>440</td>
<td>490</td>
<td>0.0026</td>
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<tr>
<td>$P_2$</td>
<td>192</td>
<td>1224</td>
<td>1220</td>
<td>0.013</td>
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<tr>
<td>$P_3$</td>
<td>226</td>
<td>484</td>
<td>532</td>
<td>0.015</td>
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<tr>
<td>$P_4$</td>
<td>226</td>
<td>484</td>
<td>0</td>
<td>0.18</td>
</tr>
</tbody>
</table>

14 TeV MSSM

arXiv:1312.3317
VH production at large m(VH)

- Considering anomalous couplings to gauge boson
- Treated here in the context of an effective field theory (EFT)
Di-higgs in VBF

\[ A(V_LV_L \rightarrow HH) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2) + \mathcal{O}(m_W^2/\hat{s}) \]

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arXiv:1611.03860
BR(H->inv) in H+X production at large p_T

- Uses missing transverse energy as a probe to higgs p_T (S/B increases with MET)

- Signal extracted using a simultaneous fit to all control regions (Z+jets, W+jets, γ+jets)

- Z->vv background constrained to the percent level using NNLO QCD/EW to relate to measured Z->ee, W and gamma spectra