Physics perspectives with future hadrons colliders

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CERN

LHCP ’20 - Online
Motivations for pp colliders beyond the LHC

• Future projects in HEP have two objectives:

  • explore the energy frontier, since solutions to known and un-explained phenomena beyond the standard model might be within reach at the next high energy collider:
    • Dark Matter
    • Neutrino mass
    • Matter-antimatter asymmetry

  • measure to high precision the physics of the electroweak symmetry breaking:
    • the shape of the Higgs potential
    • Higgs couplings, in particular to first two generations and gauge bosons → guaranteed deliverable!
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
  - $16 \, T \rightarrow 100 \, TeV$ in 100 km tunnel

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

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

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

- **Low E FCC-hh**
  - 100 km - 6T - 37 TeV

see Daniel Schulte’s presentation

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

[https://fcc-cdr.web.cern.ch/](https://fcc-cdr.web.cern.ch/)
Physics goals for a 100 TeV collider

- **Precision machine**
  - probe Higgs **self-coupling** to few % level, and %-level precision for top yukawa and 2nd generation.
  - measure **SM parameters** with high precision
  - exploit **complementarity with e^+e^-** by accessing rare decays/ **high dim.operators** (EFT) in extreme kinematic regimes (boosted)

- **Discovery machine**
  - **directly** probe new physics up to **unprecedented** scale
  - discover/exclude:
    - heavy resonances “strong” \( m(q^*) \approx 50 \text{ TeV} \), “weak” \( m(Z') \approx 40 \text{ TeV} \),
    - SUSY \( m(\text{gluino}) \approx 15 \text{ TeV} \), \( m(\text{stop}) \approx 10 \text{ TeV} \)

Physics program spans over very wide range of characters energy scales!
Inclusive SM cross sections

• Total pp cross-section and Minimum bias multiplicity show a modest increase from 14 TeV to 100 TeV

  → Levels of pile-up will scale basically as the instantaneous luminosity.

• Inclusive cross-section for relevant processes (single and HH) show a significant increase.

  • x 20-50 increase

  → interesting physics sticks out more!
Detector constraints from “threshold” physics

SM Physics produced at threshold is more forward @100TeV → in order to maintain sensitivity need large rapidity (with tracking) and low $p_T$ coverage

- **Goals:**
  - Precision spectroscopy and calorimetry up to $|\eta| < 4$
  - Tracking and calorimetry up to $|\eta| < 6$
Detector constraints from “boosted” physics

- **The boosted regime:**
  - measure leptons, jets, photons, muons originating multi-TeV resonances

  Tracking: \( \frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2} \)

  Calorimeters: \( \frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \oplus B \)

  - Tracking target: \( \sigma / p = 20\% @10 \text{ TeV} \)
  - Muons target: \( \sigma / p = 10\% @20 \text{ TeV} \)
  - Calorimeters target: containment of \( p_T = 20 \text{ TeV} \) jets

\[ \approx 11 \lambda_1 \text{ for EM + Had} \]
Detector constraints from “boosted” physics

- The boosted regime:
  - measure b-jets, taus from multi-TeV resonances
  - Long-lived particles live longer:
    - ex: 5 TeV b-Hadron travels 50 cm before decaying
      5 TeV tau lepton travels 10 cm before decaying
  - extend pixel detector further?
    - useful also for exotic topologies
      (disappearing tracks and generic BSM
      Long-lived charged particles)
  - re-think reconstruction algorithms:
    - hard to reconstruct displaced vertices
    - exploit hit multiplicity discontinuity
  - highly granular sub-detectors:
    - Tracker - pixel:10 μm @ 2cm → σ_{ηφ} ≈ 5 mrad
    - Calorimeters: 2 cm @ 2m → σ_{ηφ} ≈ 10 mrad

ex: W(10 TeV) will have decay products separated by
DR = 0.01 = 10 mrad
Why Higgs at future hadron colliders?

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

- **Large dynamic range for H production (in $p_T^H, m(H+X), \ldots$):**
  - 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 1\textsuperscript{st} order? crossover?)
Why measuring Higgs @future hadron colliders

• 100 TeV provides unique and complementary measurements to ee colliders:

  • Higgs self-coupling
  • top Yukawa
  • Higgs → invisible
  • rare decays (BR(μμ), BR(Zγ), ratios, ..) measurements will be statistically limited at FCC-ee

• Assuming, we know production xsec and luminosity, at pp colliders we measure \( \text{BR}(i) = \frac{\Gamma_i}{\Gamma_H} \)

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

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

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta \Gamma_H / \Gamma_H (%) )</td>
<td>SM</td>
<td>1.3</td>
</tr>
<tr>
<td>( \delta g_{HZZ} / g_{HZZ} (%) )</td>
<td>1.5</td>
<td>0.17</td>
</tr>
<tr>
<td>( \delta g_{HWW} / g_{HWW} (%) )</td>
<td>1.7</td>
<td>0.43</td>
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<tr>
<td>( \delta g_{Hbb} / g_{Hbb} (%) )</td>
<td>3.7</td>
<td>0.61</td>
</tr>
<tr>
<td>( \delta g_{Hcc} / g_{Hcc} (%) )</td>
<td>~70</td>
<td>1.21</td>
</tr>
<tr>
<td>( \delta g_{Hgg} / g_{Hgg} (%) )</td>
<td>2.5 (gg-&gt;H)</td>
<td>1.01</td>
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<tr>
<td>( \delta g_{Htt} / g_{Htt} (%) )</td>
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<td>( \delta g_{Hμμ} / g_{Hμμ} (%) )</td>
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</tr>
<tr>
<td>( \delta g_{HYY} / g_{HYY} (%) )</td>
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<td>3.9</td>
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<td>–</td>
</tr>
<tr>
<td>( \delta g_{HHH} / g_{HHH} (%) )</td>
<td>50</td>
<td>40</td>
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</tbody>
</table>

\( \text{BR}_{\text{exo}} \) (95%CL)  \( \text{BR}_{\text{inv}} < 2.5\% \)  \(< 1\% \)
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 $p_T(H)$: 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)

- $1\%$ lumi + theory uncertainty
- $p_T$ dependent object efficiency:
  - $\delta\varepsilon(e/\gamma) = 0.5 (1)\%$ at $p_T \to \infty$
  - $\delta\varepsilon(\mu) = 0.25 (0.5)\%$ at $p_T \to \infty$
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 $\times 10$)
  - $\times 400$ in event yields and $\times 20$ in precision
- main channels studied (using MVA):
  - $b\bar{b}\gamma\gamma$ ($\delta k_\lambda / k_\lambda \sim 3-8\%$)
  - $b\bar{b}\tau\tau$ ($\delta k_\lambda / k_\lambda \sim 12\%$)
  - $b\bar{b}ZZ(4l)$ ($\delta k_\lambda / k_\lambda \sim 15\%$)
  - $b\bar{b}b\bar{b}$ ($\delta k_\lambda / k_\lambda \sim 22\%$)
Higgs self-coupling (combination)

\[ \delta k_\lambda / k_\lambda \sim 3.0-5.5\% \text{ assuming SM couplings} \]

\[ \delta k_\lambda / k_\lambda \sim 3.0-5.5\% \text{ assuming SM couplings} \]

only 3 ab\(^{-1}\), few years of running @100 TeV to reach 10% precision

assuming SM couplings
## Summary Higgs measurements

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<td>0.65 (*)</td>
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<td>$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma} (%)$</td>
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<td>3.9</td>
<td>0.4 (*)</td>
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| $\delta g_{Htt} / g_{Htt} (\%)$    | 3.4    | –      | 0.95 (**)
| $\delta g_{HZY} / g_{HZY} (\%)$    | 9.8    | –      | 0.91 (*) |
| $\delta g_{HHH} / g_{HHH} (\%)$    | 50     | ~30 (indirect) | 5 |
| BR_{exo} (95%CL)                  | BR_{inv} < 2.5%  | < 1%   | BR_{inv} < 0.025% |

* From BR ratios wrt $B(H\to4l)$ @ FCC-ee

** From $pp\to ttH / pp\to ttZ$, using $B(H\to bb)$ and ttZ EW coupling @ FCC-ee
Higgs Self-coupling and constraints on models with 1st order EWPT

- Strong 1st order EWPT (and CP violation) needed to explain large observed baryon asymmetry in our universe
- Can be achieved with extension of SM + singlet

Direct detection of extra Higgs states

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh

Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.
W_L W_L \rightarrow \text{HH}

\begin{align*}
A(V_L V_L \rightarrow \text{HH}) & \sim \frac{\hat{s}}{v^2} (c_{2V} - c_V^2) + \mathcal{O}(m_W^2/\hat{s}), \\
& \text{high energy behaviour driven by } C_{2V} \text{ and } C_V, \text{ if } \delta C_{2V} \neq 0, \text{ grows with } E
\end{align*}

0 \text{ in the SM}

\begin{itemize}
    \item \text{negligible at large } m_{HH}
\end{itemize}

With \( c_V \) from FCC-ee, \( \delta c_{2V} < 1\% \)
**H→invisible**

- Measure it from H + X at large p_T(H)
- Fit the E_T^{miss} spectrum
- Constrain background p_T spectrum from Z→νν to the % level using NNLO QCD/EW to relate to measured Z, W and γ spectra (low stat)
- Estimate Z→νν from Z→ee/μμ control regions (high stat).

\[ \text{BR}(H\rightarrow\text{inv}) \lesssim 2.5 \times 10^{-4} \]

![Graph showing the branching ratio (BR) of H→invisible as a function of luminosity. The graph includes different models such as default, default no exp. sys, 1% unc., and 1% unc no exp sys. The graph is labeled with FCC-ee and H→ZZ→νννv.]

![Graph showing the DM-nucleon cross section as a function of DM mass. The graph includes a realistic bound with 30 ab^{-1}(100 TeV) and B(H→inv.) < 0.0002. The graph also shows various DM models such as Fermion DM, Neutrino Floor, and Neutrino Floor.]

Phil Harris
Direct searches: Heavy Resonances

- Mass reach should increase by a factor $\sim 7$ from LHC to FCC-hh
- Direct “simple” sensitivity allow to assess collider potential, and help designing detector …

“Flavour anomalies” inspired model

The FCC-hh can exclude all the allowed parameter space
Direct searches: SUSY

- stop $m = 10$ TeV
- gluino $m = 15$ TeV

Hadronic stop search

Boosted top tagger

FCC Simulation

Discovery potential (5σ)

~1.4 TeV

HL-LHC
Disappearing tracks

- Simplest WIMP DM that annihilate with EW force
- Higgsino (1 TeV), Wino (3 TeV) DM
- $\Delta m(\chi^\pm, \text{LSP}) \sim 160 \text{ MeV}/350 \text{ MeV}$
  - hardly detectable soft pion
  - leads to characteristic “disappearing track” signature

FCC-hh can discover Higgsino and Wino dark matter
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 → 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 $\delta \kappa(\text{stat}) \approx 5\%$ precision at FCC-hh (best achievable precision among all future facilities)

- Can directly and indirectly exclude compelling classes of models compatible with 1st order electro-weak phase transition

- Unprecedented reach for direct searches, heavy resonances, SUSY, Dark Matter searches
Backup
The FCC-hh detector

Barrel ECAL: LAr/Pb
\(\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\%\)
30 \(X_0\)
lat. segm: \(\Delta\eta\Delta\phi \approx 0.01\)
long. segm: 8 layers

Tracker: \(\sigma_{pT}/p_T \sim 20\%\)
at 10 TeV (1.5 m radius)

Central Magnet + Fwd solenoids

Fwd ECAL: LAr/Cu
\(\sigma_E/E \sim 30\%/\sqrt{E} \oplus 1\%\)
lat. segm: \(\Delta\eta\Delta\phi \approx 0.01\)
long. segm: 6 layers

Fwd HCAL: LAr/Cu
\(\sigma_E/E \sim 100\%/\sqrt{E} \oplus 10\%\)
lat. segm: \(\Delta\eta\Delta\phi \approx 0.05\)
long. segm: 6 layers

Barrel HCAL: Sci/Pb/Fe
\(\sigma_E/E \sim 50-60\%/\sqrt{E} \oplus 3\%\)
11 \(\lambda\) (ECAL+HCAL)
lat. segm: \(\Delta\eta\Delta\phi \approx 0.025\)
long. segm: 10 layers
Machine and detector requirements

### lumi & pile-up

<table>
<thead>
<tr>
<th>parameter</th>
<th>unit</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>FCC-hh</th>
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</thead>
<tbody>
<tr>
<td>$E_{cm}$</td>
<td>TeV</td>
<td>14</td>
<td>14</td>
<td>27</td>
<td>100</td>
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<tr>
<td>circumference</td>
<td>km</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
<td>97.8</td>
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<td>peak $\mathcal{L} \times 10^{34}$</td>
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<td>1</td>
<td>5</td>
<td>25</td>
<td>30</td>
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<td>bunch spacing</td>
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<td>25</td>
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<td>number of bunches</td>
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<td>0.3</td>
<td>3</td>
<td>10</td>
<td>30</td>
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<tr>
<td>$\sigma_{inel}$</td>
<td>mbarn</td>
<td>85</td>
<td>85</td>
<td>91</td>
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<td>$\sigma_{tot}$</td>
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<td>111</td>
<td>111</td>
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<td>BC rate</td>
<td>MHz</td>
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<td>31.6</td>
<td>31.6</td>
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<td>peak pp collision rate</td>
<td>GHz</td>
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<td>peak av. PU events/BC</td>
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<td>135</td>
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<td>997</td>
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<td>rms luminous region $\sigma_z$</td>
<td>mm</td>
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<td>time PU density</td>
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<td>$dN_{ch}/d\eta</td>
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<td>8</td>
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<td>charged tracks per collision $N_{ch}$</td>
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<td>95</td>
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<td>130</td>
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<td>Rate of charged tracks</td>
<td>GeV/c</td>
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<td>380</td>
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<td>$&lt;p_T&gt;$</td>
<td>$10^{16}$</td>
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<td>26</td>
<td>91</td>
<td>324</td>
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<tr>
<td>Number of pp collisions</td>
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<td>0.1</td>
<td>0.7</td>
<td>2.7</td>
<td>8.4 (12)</td>
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<tr>
<td>Charged part. flux at 2.5 cm est.(FLUKA)</td>
<td>GHz cm$^{-2}$</td>
<td>0.4</td>
<td>3.9</td>
<td>16.8</td>
<td>84.3 (60)</td>
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<tr>
<td>1 MeV-neq fluence at 2.5 cm est.(FLUKA)</td>
<td>$10^{16}$ cm$^{-2}$</td>
<td>1.3</td>
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<td>54</td>
<td>270 (400)</td>
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<td>Total ionising dose at 2.5 cm est.(FLUKA)</td>
<td>MGY</td>
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<td>316</td>
<td>427</td>
<td>765</td>
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<td>$E/d\eta</td>
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<td>316</td>
<td>427</td>
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<tr>
<td>$P/d\eta</td>
<td>_{\eta=5}$</td>
<td>kW</td>
<td>0.04</td>
<td>0.2</td>
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</table>

High granularity and precision timing needed to reduce occupancy levels and for pile-up rejection
Detector requirements from high $p_T$ searches

- Change in paradigm: heavy flavour tagging
- Multi-TeV $b$-Hadrons decay outside the pixel volume
- Need to adapt identification algorithms for maintaining sensitivity in high mass searches.

Only 71% of 5 TeV $b$-hadrons decay in the 5th layer.
- Displaced vertices

To be verified in high pile-up environment.

arXiv:1701:06832
Precision vs. sensitivity

- **Higher statistics shifts the balance between systematic and statistical uncertainties.** It can be exploited to define different signal regions, with better S/B, better systematics, lower impact of pile-up, pushing the potential for better measurements beyond the “systematics wall” of low-stat measurements.

- We often talk about “**precise**” Higgs measurements. What we actually aim at is “**sensitive**” tests of the Higgs properties, where sensitive refers to the ability to reveal BSM behaviours.

- **Sensitivity** may not require extreme precision. Going after “sensitivity”, rather than just precision, opens itself new opportunities.

- For example, in the context of dim. 6 operators in EFT, some operators grow with energy:

  \[ \delta O \sim \left( \frac{v}{\Lambda} \right)^2 \sim 6\% \left( \frac{\text{TeV}}{\Lambda} \right)^2 \]

  \[ \Rightarrow \text{precision probes large } \Lambda \]

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

  \[ \Rightarrow \text{kinematic reach probes large } \Lambda \]

  e.g. \( \delta O=15\% \text{ at } Q=1 \text{ TeV } \Rightarrow \Lambda \sim 2.5 \text{ TeV} \)
Higgs at large $p_T$

- 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.
Single Higgs production @FCC-hh

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

Large statistics in various Higgs decay modes 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 (relative) impact of systematic uncertainties
Higgs decays: $\gamma\gamma$ - $ZZ$ - $Z\gamma$ - $\mu\mu$

- 1% systematics on (production x luminosity), meant as a reference target. Assumes good theoretical progress over the next years, and reduction of PDF+$\alpha_S$ uncertainties with HL-LHC + FCC-ee.

- e/μ/γ efficiency systematics (shown on the right). In situ calibration, with the immense available statistics in possibly new clean channels ($Z\to\mu\mu\gamma$), will most likely reduce the uncertainties.

- All final states considered here rely on reconstruction of $m_H$ to within few GeV. Backgrounds (physics and instrumental) to be determined with great precision from sidebands (~infinite statistics)

  - Impact of pile-up: hard to estimate with today’s analyses. Focus on high-$p_T$ objects will help to decrease relative impact of pile-up

  - Following scenarios are considered:
    - $\delta_{\text{stat}}$ → stat. only (I) (signal + bkg)
    - $\delta_{\text{stat}}, \delta_{\text{eff}}$ → stat. + syst. (II)
    - $\delta_{\text{stat}}, \delta_{\text{eff}}, \delta_{\text{prod}} = 1\%$ → stat. + syst. + prod (III)

- e/μ/γ efficiency systematics (shown on the right). In situ calibration, with the immense available statistics in possibly new clean channels ($Z\to\mu\mu\gamma$), will most likely reduce the uncertainties.
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%
Standalone 100 TeV Higgs measurements

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

\[
\frac{\sigma(WH[\rightarrow \gamma\gamma])}{\sigma(WZ[\rightarrow e^+e^-])} \quad \frac{\sigma(WH[\rightarrow \tau\tau])}{\sigma(WZ[\rightarrow \tau\tau])} \quad \frac{\sigma(WH[\rightarrow bb])}{\sigma(WZ[\rightarrow bb])}
\]

\[
G_W = g^2_{HWW} \times BR(H \rightarrow \gamma\gamma) \quad G_\tau = g^2_{HWW} \times BR(H \rightarrow \tau\tau) \quad G_b = g^2_{HWW} \times BR(H \rightarrow bb)
\]

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

also: \(\sigma(Z[\nu\nu]H[\rightarrow \gamma\gamma]) / \sigma(Z[\nu\nu]Z[\rightarrow e^+e^-])\)
Vector Boson Scattering

- Sets constraints on detector acceptance (fwd jets at $\eta \approx 4$)
- Study $W^+/W^- (\text{same-sign})$ channel
- Large $WZ$ background at FCC-hh
- 3-4% precision on $W_LW_L$ scattering xsec. achievable with full dataset (only $3\sigma$ HL-LHC)
- Indirect measurement of $HWW$ coupling possible, $\delta\kappa_W/\kappa_W \approx 2\%$

Table 4.5: Constraints on the $HWW$ coupling modifier $\kappa_W$ at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_LW_L \rightarrow HH$ process.

<table>
<thead>
<tr>
<th>$m_{l^+l^+}$ cut</th>
<th>$&gt; 50$ GeV</th>
<th>$&gt; 200$ GeV</th>
<th>$&gt; 500$ GeV</th>
<th>$&gt; 1000$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_W \in$</td>
<td>[0.98,1.05]</td>
<td>[0.99,1.04]</td>
<td>[0.99,1.03]</td>
<td>[0.98,1.02]</td>
</tr>
</tbody>
</table>
Strong 1\textsuperscript{st} order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking.

**Strong 1\textsuperscript{st} order phase transition \Rightarrow \langle \Phi_C \rangle > T_C**

In the SM this requires $m_H \lesssim 80$ GeV, else transition is a smooth crossover.

Since $m_H = 125$ GeV, new physics, coupling to the Higgs and effective at scales $\mathcal{O}(\text{TeV})$, must modify the Higgs potential to make this possible.

- Probe higher-order terms of the Higgs potential (selfcouplings)
- Probe the existence of other particles coupled to the Higgs
MSSM Higgs

N. Craig, J. Hajer, Y.-Y. Li, T. Liu, H. Zhang, 
arXiv:1605.08744

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, 
arXiv:1504.07617
Heavy resonances (summary)