Higgs at future hadron colliders

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Outline

• Where we are (LHC - Run II)
  • Where we will be (Run III - HL-LHC)…

• Future colliders:
  • Future hadron vs. $e^+e^-$ colliders
  • Rates at 100 TeV vs 14 TeV
  • Experimental constraints:
    • threshold vs boosted production
    • Synergies and complementarities between hadron vs. $e^+e^-$ colliders

• Higgs measurements at future hadron colliders:
  • Single Higgs
  • Double Higgs
  • Indirect measurements
  • BSM
The Higgs sector

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \]
\[ + i \bar{\psi} \gamma^\mu \psi + h.c. \]
\[ + \bar{\Psi}_{ij} \Psi_{ij} \phi + h.c. \]
\[ + \Box \phi \phi^2 - V(\phi) \]

\[ \mathcal{L}_{H-f} = -\sum_f \frac{m_f}{v} \bar{f} f H \]

fermion couplings

Higgs potential

\[ \frac{2M_W^2}{v} \]

\[ \frac{3m_H}{v} \]

\[ \frac{3m_H^2}{v^2} \]
Present state of affairs

Higgs mass

2012 — Discovery

> 2021 — Precision

Higgs couplings

cf. Marumi Kado
(Near) future state of affairs - HLLHC

cf. Maria Cepeda

Need to improve upon LHC precision measurements:

- Light couplings (charm, muon)
- Invisible decays, total width
- Self-coupling(s)
- BSM Higgs
Future $e^+e^-$ machines

**FCC-ee**

- Maximum $E_{CM} \sim 350$ GeV (limited by synchrotron radiation)
- Very high luminosity at low energy ($Z > W > H > t$)
- Allows multiple experiments

**CEPC**

- Can reach high energies
- High luminosity at high energies ($ttH, HH, H \ldots$)

**CLIC**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$Z$</th>
<th>$W$</th>
<th>$H$</th>
<th>$t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Cm E$ [GeV]</td>
<td>91.2</td>
<td>160</td>
<td>240</td>
<td>350</td>
</tr>
<tr>
<td>FCC-ee</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$L$ [10^{34} cm^{-2}s^{-1}]</td>
<td>200</td>
<td>28</td>
<td>8.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Years op.</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Int. $L/2$ IP [ab^{-1}]</td>
<td>150</td>
<td>10</td>
<td>5</td>
<td>1.5</td>
</tr>
<tr>
<td>CEPC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L$ [10^{34} cm^{-2}s^{-1}]</td>
<td>32</td>
<td>10</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Years op.</td>
<td>2</td>
<td>1</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Int. $L/2$ IP [ab^{-1}]</td>
<td>16</td>
<td>2.6</td>
<td>5.6</td>
<td></td>
</tr>
</tbody>
</table>

**ILC**

- $\sqrt{s}$ | 500 GeV | 1 TeV |
- Lumi | 4 ab^{-1} | 8 ab^{-1} |

---

- $\sqrt{s}$ | 1.5 TeV | 3 TeV |
- Lumi | 2.5 ab^{-1} | 5 ab^{-1} |
Possible future colliders: pp

Pros:

• high center of mass, not limited by synchrotron radiation $\sim (m_e/m_p)^4$
• high luminosity $\rightarrow$ high rates
• large cross-sections for strong production

Cons:

• large backgrounds QCD ($\alpha_S \sim 10 \alpha_{EM}$)
• collide partons (not all ECM available)
• pile-up (due to high lumi)

For fixed size, limited only by field strength $B$

• Discovery machines for heavy new states
• Thanks to high rates, well suited for precision
Future hadron colliders

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

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

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

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

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

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

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

[https://fcc-cdr.web.cern.ch/](https://fcc-cdr.web.cern.ch/)
High energy hadron machines

<table>
<thead>
<tr>
<th>HE-LHC</th>
<th>LE-FCC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>sqrt(s) 27 TeV</td>
<td>sqrt(s) 37 TeV</td>
<td>sqrt(s) 100 TeV</td>
</tr>
<tr>
<td>Lumi 15 ab⁻¹</td>
<td>Lumi 15 ab⁻¹</td>
<td>Lumi 30 ab⁻¹</td>
</tr>
<tr>
<td>B 16 T</td>
<td>B 6 T</td>
<td>B 16 T</td>
</tr>
<tr>
<td>circ. 27 km</td>
<td>circ. 100 km</td>
<td>circ. 100 km</td>
</tr>
</tbody>
</table>

will focus on the FCC-hh.
### Machine specs 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>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{cm}$</td>
<td>TeV</td>
<td>14</td>
<td>14</td>
<td>27</td>
<td>100</td>
</tr>
<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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<tr>
<td>peak $\mathcal{L} \times 10^{34}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>1</td>
<td>5</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>bunch spacing</td>
<td>ns</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>number of bunches</td>
<td></td>
<td>2808</td>
<td>2808</td>
<td>2808</td>
<td>10600</td>
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<td>goal $\int \mathcal{L}$</td>
<td>ab$^{-1}$</td>
<td>0.3</td>
<td>3</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>$\sigma_{inel}$</td>
<td>mbarn</td>
<td>85</td>
<td>85</td>
<td>91</td>
<td>108</td>
</tr>
<tr>
<td>$\sigma_{tot}$</td>
<td>mbarn</td>
<td>111</td>
<td>111</td>
<td>126</td>
<td>153</td>
</tr>
<tr>
<td>BC rate</td>
<td>MHz</td>
<td>31.6</td>
<td>31.6</td>
<td>31.6</td>
<td>32.5</td>
</tr>
<tr>
<td>peak pp collision rate</td>
<td>GHz</td>
<td>0.85</td>
<td>4.25</td>
<td>22.8</td>
<td>32.4</td>
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<tr>
<td>peak av. PU events/BC</td>
<td></td>
<td>27</td>
<td>135</td>
<td>721</td>
<td>997</td>
</tr>
<tr>
<td>rms luminous region $\sigma_z$</td>
<td>mm</td>
<td>45</td>
<td>57</td>
<td>57</td>
<td>49</td>
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<tr>
<td>line PU density</td>
<td>mm$^{-1}$</td>
<td>0.2</td>
<td>0.9</td>
<td>5</td>
<td>8.1</td>
</tr>
<tr>
<td>time PU density</td>
<td>ps$^{-1}$</td>
<td>0.1</td>
<td>0.28</td>
<td>1.51</td>
<td>2.43</td>
</tr>
<tr>
<td>$dN_{ch}/d\eta</td>
<td>_{\eta=0}$</td>
<td></td>
<td>7</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>charged tracks per collision $N_{ch}$</td>
<td>GHz</td>
<td>95</td>
<td>95</td>
<td>108</td>
<td>130</td>
</tr>
<tr>
<td>Rate of charged tracks</td>
<td>GHz</td>
<td>76</td>
<td>380</td>
<td>2500</td>
<td>4160</td>
</tr>
<tr>
<td>$&lt;p_T&gt;$</td>
<td>GeV/c</td>
<td>0.6</td>
<td>0.6</td>
<td>0.7</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Number of pp collisions: 10$^{16}$

Charged part. flux at 2.5 cm est. (FLUKA) $10^{16}$ cm$^{-2}$

1 MeV-neq fluence at 2.5 cm est. (FLUKA) $10^{16}$ cm$^{-2}$

Total ionising dose at 2.5 cm est. (FLUKA) MGy

$E/d\eta|_{\eta=5}$ $dE/d\eta|_{\eta=5}$ kW

$P/d\eta|_{\eta=5}$ $dP/d\eta|_{\eta=5}$ kW

LHC: 30 PU events/bc
HL-LHC: 140 PU events/bc
FCC-hh: 1000 PU events/bc

but also $\times 10$ integrated luminosity w.r.t to HL-LHC

High granularity and precision timing needed to reduce occupancy levels and for pile-up rejection
Reach at high energies (I)

To compute reach, we assume we need to observe a given number of events:

\[ N = \sigma L \]

\[ \sigma \sim L_{\text{parton}}(\tau) \cdot \sigma_{\text{partonic}} \]

\[ \frac{1}{\tau^a} \]

\[ \tau = x_1 x_2 = \frac{M^2}{s} \]

\( L \sim \frac{1}{\tau^3} \)

- \( L \): integrated luminosity
- \( L_{\text{parton}} \): parton luminosity
- \( \sigma \approx 2 \)
- \( a \approx 6 \)
Reach at high energies (II)

How does the reach for observing a new state of mass $M$ (e.g. BSM Higgs, ...) scale from 14 TeV to 100 TeV?

Assume we need the same number of events at 14 TeV and 100 TeV to claim discovery:

\[
\# \text{ events } (\sqrt{s}_2 = 100 \text{ TeV}) \approx \# \text{ events } (\sqrt{s}_1 = 14 \text{ TeV})
\]

\[
\frac{M_{100 \text{ TeV}}}{M_{14 \text{ TeV}}} \approx 7
\]

As expected, mass reach scales linearly with $\sqrt{s}$
Reach at high energies (III)

How does the rate of a given process (e.g. single Higgs production) scale from 14 TeV to 100 TeV

cross-section ($\sqrt{s} = 100$ TeV) ≈ $L_1 / L_2 ≈ (s_2 / s_1)^a ≈ (100 / 14)^2a$
cross-section ($\sqrt{s} = 14$ TeV)

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma(100)/\sigma(14)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH</td>
<td>15</td>
</tr>
<tr>
<td>HH</td>
<td>40</td>
</tr>
<tr>
<td>ttH</td>
<td>55</td>
</tr>
<tr>
<td>$H (p_T &gt; 1$ TeV)</td>
<td>400</td>
</tr>
</tbody>
</table>

Very large rate increase by increasing center of mass energy

NB: this improvement only comes from the cross-section (neglects integrated luminosity)
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!
Huge statistics allow for **great potential of further exploration of SM particles at 100 TeV**
Higgs @threshold

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 $|\eta| < 6$

$x_{\text{min}} \sim M^2 / \text{s}$
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.

- **highly granular sub-detectors:**
  - Tracker - pixel: 10 μm @ 2cm → $\sigma_{\eta\phi} \approx 5$ mrad
  - Calorimeters: 2 cm @ 2m → $\sigma_{\eta\phi} \approx 10$ mrad

- good energy/$p_T$ resolution at large $p_T$:
  - $\sigma_p / p = 2\% @ 1$ TeV
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: \( \sigma_{p_T}/p_T \sim 20\% \)

at 10 TeV (1.5 m radius)

Central Magnet + Fwd solenoids

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

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

9 m
23 m
Recap: Higgs @ e+e- colliders

- Higgs tagged by a Z, Higgs mass from Z recoil

\[ m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-) \]

Higgs recoil mass measurement → production cross section:

- \( 10^6 \) Higgs produced @ FCC-ee
  - rate \( \sim g_Z^2 \) → \( \delta g_Z/g_Z \) \( \sim 0.1 \% \)

- Then measure \( ZH \rightarrow ZZZ \)
  - rate \( \sim g_Z^4 / \Gamma_H \) → \( \delta \Gamma_H / \Gamma_H \) \( \sim 1 \% \)

- Then measure \( ZH \rightarrow ZXX \)
  - rate \( \sim g_Z^2 g_X^2 / \Gamma_H \) → \( \delta g_X/g_X \) \( \sim 1 \% \)

provides absolute \( g_Z \) coupling in e+e-

BUT limited statistics:

- for rare decay modes
- HH production
Coupling measurements at ee vs hh

At pp colliders we can only measure:

\[ \sigma_{\text{prod}} \cdot \text{BR}(i) = \sigma_{\text{prod}} \cdot \frac{\Gamma_i}{\Gamma_H} \]

\[ \rightarrow \text{we do not know the total width.} \]

In order to perform global fits, we have to make \textit{model-dependent assumptions}.

Instead, by performing measurements of ratios of BRs at hadron colliders:

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

We can “convert” \textit{relative measurements into absolute} via \( g_Z \) thanks to \( e^+e^- \) measurement.

\[ \rightarrow \text{synergy between lepton and hadron colliders} \]
Why measuring Higgs @100TeV?

• 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

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC (%)</th>
<th>FCC-ee (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>δΓ_H / Γ_H (%)</td>
<td>SM</td>
<td>1.3</td>
</tr>
<tr>
<td>δg_HZZ / g_HZZ (%)</td>
<td>1.5</td>
<td>0.17</td>
</tr>
<tr>
<td>δg_HWW / g_HWW (%)</td>
<td>1.7</td>
<td>0.43</td>
</tr>
<tr>
<td>δg_Hbb / g_Hbb (%)</td>
<td>3.7</td>
<td>0.61</td>
</tr>
<tr>
<td>δg_Hcc / g_Hcc (%)</td>
<td>~70</td>
<td>1.21</td>
</tr>
<tr>
<td>δg_Hgg / g_Hgg (%)</td>
<td>2.5 (gg→H)</td>
<td>1.01</td>
</tr>
<tr>
<td>δg_Hττ / g_Hττ (%)</td>
<td>1.9</td>
<td>0.74</td>
</tr>
<tr>
<td>δg_Hμμ / g_Hμμ (%)</td>
<td>4.3</td>
<td>9.0</td>
</tr>
<tr>
<td>δg_HYY / g_HYY (%)</td>
<td>1.8</td>
<td>3.9</td>
</tr>
<tr>
<td>δg_Htt / g_Htt (%)</td>
<td>3.4</td>
<td>–</td>
</tr>
<tr>
<td>δg_HZγ / g_HZγ (%)</td>
<td>9.8</td>
<td>–</td>
</tr>
<tr>
<td>δg_HHH / g_HHH (%)</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>

BR_{exo} (95%CL) = BR_{inv} < 2.5% < 1%

Large rates for rare modes and HH production at FCC-hh

→ complementary to e^+e^−
Higgs physics at future hadron colliders

- **Large Higgs production rates:**
  - 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?)
Single Higgs production @FCC-hh

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$(13 TeV)</th>
<th>$\sigma$(100 TeV)</th>
<th>$\sigma$(100)/$\sigma$(13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH (N^3LO)</td>
<td>49 pb</td>
<td>803 pb</td>
<td>16</td>
</tr>
<tr>
<td>VBF (N^3LO)</td>
<td>3.8 pb</td>
<td>69 pb</td>
<td>16</td>
</tr>
<tr>
<td>VH (N^3LO)</td>
<td>2.3 pb</td>
<td>27 pb</td>
<td>11</td>
</tr>
<tr>
<td>ttH (N^3LO)</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 channels, to isolate cleaner samples in regions (e.g. @large Higgs $p_T$) with:
  - higher S/B
  - smaller (relative) impact of systematic uncertainties

$N_{100} = \sigma_{100 \text{ TeV}} \times 20 \text{ ab}^{-1}$
$N_{8} = \sigma_{8 \text{ TeV}} \times 20 \text{ fb}^{-1}$
$N_{14} = \sigma_{14 \text{ TeV}} \times 3 \text{ ab}^{-1}$

Factor: 1/100 1/10
reduction in stat. unc.
Top Yukawa (production)

- production ratio $\sigma(\text{ttH})/\sigma(\text{ttZ}) \approx y_t^2 y_b^2/ g_{\text{ttZ}}^2$
- measure $\sigma(\text{ttH})/\sigma(\text{ttZ})$ in $\text{H/Z}\rightarrow\text{bb}$ 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 $g_{\text{ttZ}}$ and $\kappa_b$ known to 1% (from FCC-ee),

$\rightarrow$ measure $y_t$ to 1%
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.

- $e/\mu/\gamma$ efficiency systematics (shown on the right). In situ calibration, with the immense available statistics in possibly new clean channels ($Z\rightarrow\mu\mu\gamma$), 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)
Higgs decays (signal strenth)

- study sensitivity as a function of minimum \( p_T(H) \) requirement in the \( \gamma\gamma, ZZ(4l), \mu\mu \) and \( Z(\ell\ell)\gamma \) 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)

\[
\delta \mu / \mu = 1\% \text{ lumi + theory uncertainty}
\]

\[
\delta \epsilon(e/\gamma) = 0.5 (1)\% \text{ at } p_T \to \infty
\]

\[
\delta \epsilon(\mu) = 0.25 (0.5)\% \text{ at } p_T \to \infty
\]
Ratios of $\text{BR}(H \rightarrow XX) / \text{BR}(H \rightarrow ZZ)$

- 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 0.2%)
**H → invisible**

- Measure it from H + X at large $p_T(H)$
- Fit the $E_T^{miss}$ spectrum
- Constrain background $p_T$ spectrum from $Z \rightarrow \nu\nu$ to the % level using NNLO QCD/EW to relate to measured Z, W and $\gamma$ spectra (low stat)
- Estimate $Z \rightarrow \nu\nu$ ($W \rightarrow l\nu$) from $Z \rightarrow e\mu$ ($W \rightarrow l\nu$) control regions (high stat).

![Graph showing BR(H→inv) ≈ 2.5 \times 10^{-4} for FCC-ee](image)

**Phil Harris**

- $BR(H \rightarrow inv) \approx 2.5 \times 10^{-4}$
- 30 ab$^{-1}$

**FCC-ee**

**H → ZZ → vvvv**
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**:

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

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

### Parton Level Study

| \( p_T^{\min} \) (GeV) | \(|W[eZ[e]|\times L\) | \(|W[eH]|\times L\) | \(|W[\ell Z[\ell]|\times L\) | \(|W[\ell H[\ell]|\times L\) | \(|\delta R/R\) |
|--------------------------|----------------|----------------|----------------|----------------|---------------|
| 100                      | 2.1E-2         | 1.0E-1         | 1.3E6          | 1.4E4          | 8.5E-3        |
| 150                      | 1.0E-2         | 6.3E-2         | 6.0E5          | 8.7E3          | 1.1E-2        |
| 200                      | 5.6E-3         | 3.8E-2         | 3.4E5          | 5.2E3          | 1.4E-2        |
| 300                      | 2.1E-3         | 1.6E-2         | 1.3E5          | 2.2E3          | 2.1E-2        |

\[\delta G/G < 1\%\]
Why the Higgs self-coupling?

\[ \mathcal{L}_h = m_h^2 h^2 + \lambda_3 h^3 + \lambda_4 h^4 \]

- In the SM, EWSB and \( \lambda_3 \) and \( \lambda_4 \) purely determined by the **shape of the Higgs potential**
- However, Higgs potential could be different (required by some scenarios of EWK baryogenesis) \( \rightarrow \) **has barely been measured**
- Measuring the Higgs self-couplings gives a handle on the Higgs potential is determined by the self coupling value
Higgs self-coupling

**HL-LHC**

- 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 Lx10)
  - x400 in event yields and x20 in precision
- Main channels studied:
  - $bb\gamma\gamma$ (most sensitive - discussed here)
  - $bb\tau\tau$
  - $bbZZ(4l)$
  - $bbb$
Higgs pair production at the FCC-hh

\[ \sigma \approx 1 \text{ pb} \]

gluon fusion

vbf HH:

VHH:

ttHH:

Expected precision:

\[ \delta \kappa_\lambda = \frac{\delta \mu}{\frac{d\mu}{d\kappa_\lambda}} \]

where:

\[ \kappa_\lambda = \frac{\lambda_3}{\lambda_3^{\text{SM}}} \]

\[ \mu = \frac{\sigma}{\sigma_{\text{SM}}} \]

~ 1
The di-Higgs invariant mass spectrum $m_{HH}$ is highly sensitive to the self-coupling parameter.
Self-coupling at the FCC-hh

• Channels:
  • $\gamma\gamma$ (golden channel)
  • $\tau\tau$
  • $b\bar{b}$
  • $b\bar{b}Z\bar{Z}(4l)$

• Defined 3 scenarios with various detector assumptions and systematics:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scenario I</th>
<th>Scenario II</th>
<th>Scenario III</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$-jet ID eff.</td>
<td>82-65%</td>
<td>80-63%</td>
<td>78-60%</td>
</tr>
<tr>
<td>$b$-jet c mistag</td>
<td>15-3%</td>
<td>15-3%</td>
<td>15-3%</td>
</tr>
<tr>
<td>$b$-jet l mistag</td>
<td>1-0.1%</td>
<td>1-0.1%</td>
<td>1-0.1%</td>
</tr>
<tr>
<td>$\tau$-jet ID eff.</td>
<td>80-70%</td>
<td>78-67%</td>
<td>75-65%</td>
</tr>
<tr>
<td>$\tau$-jet mistag (jet)</td>
<td>2-1%</td>
<td>2-1%</td>
<td>2-1%</td>
</tr>
<tr>
<td>$\tau$-jet mistag (ele)</td>
<td>0.1-0.04%</td>
<td>0.1-0.04%</td>
<td>0.1-0.04%</td>
</tr>
<tr>
<td>$\gamma$ ID eff.</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>jet $\rightarrow \gamma$ eff.</td>
<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>$m_{\gamma\gamma}$ resolution [GeV]</td>
<td>1.2</td>
<td>1.8</td>
<td>2.9</td>
</tr>
<tr>
<td>$m_{b\bar{b}}$ resolution [GeV]</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>
Self-coupling at the FCC-hh

• Expected precision:

<table>
<thead>
<tr>
<th></th>
<th>scenario I</th>
<th>scenario II</th>
<th>scenario III</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bb\gamma\gamma$</td>
<td>3.8</td>
<td>5.9</td>
<td>10.0</td>
</tr>
<tr>
<td>$bb\tau\tau$</td>
<td>9.8</td>
<td>12.2</td>
<td>13.8</td>
</tr>
<tr>
<td>$bbbb$</td>
<td>22.3</td>
<td>27.1</td>
<td>32.0</td>
</tr>
<tr>
<td>comb.</td>
<td>3.4</td>
<td>5.1</td>
<td>7.8</td>
</tr>
</tbody>
</table>

• Combined precision:

- **3.5-8%** for SM (3% stat. only)
- **10-20%** for $\lambda_3 = 1.5 \times \lambda_3^{\text{SM}}$
Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

- $\delta k_\lambda^{\text{stat+syst}} (k_\lambda = 1.5) \approx 10 \%$
- $\delta k_\lambda^{\text{stat+syst}} (k_\lambda = 1.7) \approx 15 \%$
- $\delta k_\lambda^{\text{stat+syst}} (k_\lambda = 2.0) \approx 20 \%$

CAVEAT: assumes all SM-like couplings except for trilinear
Summary of Higgs direct measurements

<table>
<thead>
<tr>
<th>Observable</th>
<th>Parameter</th>
<th>Precision (stat.)</th>
<th>Precision (stat.+syst.+lumi.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu = \sigma(H) \times B(H \rightarrow \gamma\gamma)$</td>
<td>$\delta \mu/\mu$</td>
<td>0.1%</td>
<td>1.45%</td>
</tr>
<tr>
<td>$\mu = \sigma(H) \times B(H \rightarrow \mu\mu)$</td>
<td>$\delta \mu/\mu$</td>
<td>0.28%</td>
<td>1.22%</td>
</tr>
<tr>
<td>$\mu = \sigma(H) \times B(H \rightarrow 4\mu)$</td>
<td>$\delta \mu/\mu$</td>
<td>0.18%</td>
<td>1.85%</td>
</tr>
<tr>
<td>$\mu = \sigma(H) \times B(H \rightarrow \gamma\mu\mu)$</td>
<td>$\delta \mu/\mu$</td>
<td>0.55%</td>
<td>1.61%</td>
</tr>
<tr>
<td>$\mu = \sigma(HH) \times B(H \rightarrow \gamma\gamma) \times B(H \rightarrow b\bar{b})$</td>
<td>$\delta \lambda/\lambda$</td>
<td>5%</td>
<td>7.0%</td>
</tr>
<tr>
<td>$R = B(H \rightarrow \mu\mu)/B(H \rightarrow 4\mu)$</td>
<td>$\delta R/R$</td>
<td>0.33%</td>
<td>1.3%</td>
</tr>
<tr>
<td>$R = B(H \rightarrow \gamma\gamma)/B(H \rightarrow 2e2\mu)$</td>
<td>$\delta R/R$</td>
<td>0.17%</td>
<td>0.8%</td>
</tr>
<tr>
<td>$R = B(H \rightarrow \gamma\gamma)/B(H \rightarrow 2\mu)$</td>
<td>$\delta R/R$</td>
<td>0.29%</td>
<td>1.38%</td>
</tr>
<tr>
<td>$R = B(H \rightarrow \mu\mu\gamma)/B(H \rightarrow 4\mu)$</td>
<td>$\delta R/R$</td>
<td>0.58%</td>
<td>1.82%</td>
</tr>
<tr>
<td>$R = \sigma(t\bar{t}H) \times B(H \rightarrow b\bar{b})/\sigma(t\bar{t}Z) \times B(Z \rightarrow b\bar{b})$</td>
<td>$\delta R/R$</td>
<td>1.05%</td>
<td>1.9%</td>
</tr>
<tr>
<td>$B(H \rightarrow \text{invisible})$</td>
<td>$B@95%CL$</td>
<td>$1 \times 10^{-4}$</td>
<td>$2.5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\delta R/R$</th>
<th>HE-LHC</th>
<th>LE-FCC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R = B(H \rightarrow \gamma\gamma)/B(H \rightarrow 2e2\mu)$</td>
<td>1.7%</td>
<td>1.5%</td>
<td>0.8%</td>
</tr>
<tr>
<td>$R = B(H \rightarrow \mu\mu)/B(H \rightarrow 4\mu)$</td>
<td>3.6%</td>
<td>2.9%</td>
<td>1.3%</td>
</tr>
<tr>
<td>$R = B(H \rightarrow \mu\mu\gamma)/B(H \rightarrow \mu\mu)$</td>
<td>8.4%</td>
<td>6%</td>
<td>1.8%</td>
</tr>
<tr>
<td>$R = B(H \rightarrow \gamma\gamma)/B(H \rightarrow 2\mu)$</td>
<td>3.5%</td>
<td>2.8%</td>
<td>1.4%</td>
</tr>
</tbody>
</table>

- Percent level precision on $\sigma \times BR$ in most rare decay channels achievable only at 100 TeV
- Percent level precision on couplings if HZZ coupling known from FCC-ee (to 0.2%)
## Summary direct measurements

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC</th>
<th>FCC-ee</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta \Gamma_H / \Gamma_H (%)$</td>
<td>SM</td>
<td>1.3</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{HZZ} / g_{HZZ} (%)$</td>
<td>1.5</td>
<td>0.17</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{HWW} / g_{HWW} (%)$</td>
<td>1.7</td>
<td>0.43</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{Hbb} / g_{Hbb} (%)$</td>
<td>3.7</td>
<td>0.61</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{Hcc} / g_{Hcc} (%)$</td>
<td>~70</td>
<td>1.21</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{Hgg} / g_{Hgg} (%)$</td>
<td>2.5 (gg-&gt;H)</td>
<td>1.01</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{H\tau\tau} / g_{H\tau\tau} (%)$</td>
<td>1.9</td>
<td>0.74</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{H\mu\mu} / g_{H\mu\mu} (%)$</td>
<td>4.3</td>
<td>9.0</td>
<td>0.65 (*)</td>
</tr>
<tr>
<td>$\delta g_{HYY} / g_{HYY} (%)$</td>
<td>1.8</td>
<td>3.9</td>
<td>0.4 (*)</td>
</tr>
<tr>
<td>$\delta g_{Htt} / g_{Htt} (%)$</td>
<td>3.4</td>
<td>–</td>
<td>0.95 (**)</td>
</tr>
<tr>
<td>$\delta g_{HZY} / g_{HZY} (%)$</td>
<td>9.8</td>
<td>–</td>
<td>0.91 (*)</td>
</tr>
<tr>
<td>$\delta g_{HHH} / g_{HHH} (%)$</td>
<td>50</td>
<td>~30 (indirect)</td>
<td>5</td>
</tr>
<tr>
<td>BR_{exo} (95%CL)</td>
<td>BR_{inv} &lt; 2.5%</td>
<td>&lt; 1%</td>
<td>BR_{inv} &lt; 0.025%</td>
</tr>
</tbody>
</table>

* 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
**Vector Boson Scattering**

- Sets constraints on detector acceptance (fwd jets at η≈4)
- Study $W^+/W^- (\text{same-sign})$ channel
- Large WZ background at FCC-hh
- 3-4% precision on $W_L W_L$ scattering xsec. achievable with full dataset (only 3σ 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 $W_L W_L \to HH$ 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>
$W_L W_L \rightarrow HH$

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

With $c_V$ from FCC-ee, $\delta c_{2V} < 1\%$

High energy behaviour driven by $C_{2V}$ and $C_V$, if $\delta C_{2V} \neq 0$, grows with $E$
Higgs Self-coupling and constraints on models with 1st order EWPT  

- Strong 1st order electroweak phase transition (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.
Conclusions & outlook

- A future 100 TeV 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, 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 $\delta k_\lambda(\text{stat}) \approx 5\%$ precision at FCC-hh (best achievable precision among all future facilities).

- **VBS** longitudinal polarisations $V_L V_L$ can be measured at 3-4% precision ($W_L W_L$ same sign), provides percent level precision $k_W$ coupling measurement.

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

- Extremely rich Higgs program at the FCC-hh, goes much beyond what has been presented here.

- Further studies are needed:
  - direct Higgs width measurement
  - 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
  - VH production at large mass
  - missing HH decay channels (bbbb, etc ...) and final combination
  - CP violation
Backup
Motivations for pp colliders beyond the LHC

• Future projects in HEP have two objectives:

  • explore the energy frontier, as solutions to known and unexplained 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!
Possible future colliders: FCC-hh

- Circumference = 100 km
- Need dipoles that generate \( B = 16 \, \text{T} \)

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

8 GJ kinetic energy per beam
- Airbus A380 at 720 km/h
- 2000 kg TNT
- \( O(20) \) times LHC

### Table: FCC-hh Initial vs. Ultimate

<table>
<thead>
<tr>
<th></th>
<th>FCC-hh Initial</th>
<th>FCC-hh Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity ( L ) ([10^{34} \text{cm}^2\text{s}^{-1}])</td>
<td>5</td>
<td>20-30</td>
</tr>
<tr>
<td>Background events/bx</td>
<td>170 (34)</td>
<td>&lt;1020 (204)</td>
</tr>
<tr>
<td>Bunch distance ( \Delta t ) ( [\text{ns}] )</td>
<td>25 (5)</td>
<td></td>
</tr>
<tr>
<td>Bunch charge ( N ) ([10^{11}])</td>
<td>1 (0.2)</td>
<td></td>
</tr>
<tr>
<td>Fract. of ring filled ( \eta_{\text{fill}} ) ( [%] )</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Norm. emitt. ([\mu\text{m}])</td>
<td>2.2 (0.44)</td>
<td></td>
</tr>
<tr>
<td>Max ( \xi ) for 2 IPs</td>
<td>0.01 (0.02)</td>
<td>0.03</td>
</tr>
<tr>
<td>IP beta-function ( \beta ) ([\text{m}])</td>
<td>1.1</td>
<td>0.3</td>
</tr>
<tr>
<td>IP beam size ( \sigma ) ([\mu\text{m}])</td>
<td>6.8 (3)</td>
<td>3.5 (1.6)</td>
</tr>
<tr>
<td>RMS bunch length ( \sigma_x ) ([\text{cm}])</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Crossing angle ([\sigma_x])</td>
<td>12</td>
<td>Crab. Cav.</td>
</tr>
<tr>
<td>Turn-around time ([\text{h}])</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

In its high luminosity phase, FCC-hh produces **1000 PU interactions** per bunch crossing.
Table S.1: Key FCC-hh baseline parameters compared to LHC and HL-LHC parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Nominal</td>
<td></td>
</tr>
<tr>
<td><strong>Physics performance and beam parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak luminosity$^1$ [10$^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>1.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Optimum average integrated luminosity / day [fb$^{-1}$]</td>
<td>0.47</td>
<td>2.8</td>
<td>2.2</td>
</tr>
<tr>
<td>Assumed turnaround time [h]</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Target turnaround time [h]</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Peak number of inelastic events / crossing</td>
<td>27</td>
<td>135</td>
<td>171</td>
</tr>
<tr>
<td>Total / inelastic cross section $\sigma$ proton [mbarn]</td>
<td>111 / 85</td>
<td>153 / 108</td>
<td></td>
</tr>
<tr>
<td>Luminous region RMS length [cm]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance IP to first quadrupole, $L^*$ [m]</td>
<td>23</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td><strong>Beam parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of bunches $n$</td>
<td>2808</td>
<td></td>
<td>10400</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Bunch population $N$ [10$^{11}$]</td>
<td>1.15</td>
<td>2.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Nominal transverse normalised emittance [µm]</td>
<td>3.75</td>
<td>2.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Number of IPs contributing to $\Delta Q$</td>
<td>3</td>
<td>2</td>
<td>2+2</td>
</tr>
<tr>
<td>Maximum total b-b tune shift $\Delta Q$</td>
<td>0.01</td>
<td>0.015</td>
<td>0.011</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>0.584</td>
<td>1.12</td>
<td>0.5</td>
</tr>
<tr>
<td>RMS bunch length$^2$ [cm]</td>
<td></td>
<td></td>
<td>7.55</td>
</tr>
<tr>
<td>IP beta function [m]</td>
<td>0.55</td>
<td>0.15 (min)</td>
<td>1.1</td>
</tr>
<tr>
<td>RMS IP spot size [µm]</td>
<td>16.7</td>
<td>7.1 (min)</td>
<td>6.8</td>
</tr>
<tr>
<td>Full crossing angle [µrad]</td>
<td>285</td>
<td>590</td>
<td>104</td>
</tr>
</tbody>
</table>

$^1$ For the nominal parameters, the peak luminosity is reached during the run.

$^2$ The HL-LHC assumes a different longitudinal distribution; the equivalent Gaussian is 9 cm.

$^3$ The crossing angle will be compensated using the crab crossing scheme.
The FCC project (rationale)

- HL-LHC data-taking ends in 2035
- Build a 100 km tunnel
- If magnets are ready by ~ 2040 go for FCC-hh
- If not FCC-ee ~20 yrs
- then FCC-hh ~20 yrs

100 km tunnel ensures HEP field activities for ~ 60 yrs
FCC-ee → FCC-hh → FCC-xx (x=μ)
Long term accelerator complex easier to fund on flat budget

<table>
<thead>
<tr>
<th>Domain</th>
<th>Cost in MCHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1 - Civil Engineering</td>
<td>5,400</td>
</tr>
<tr>
<td>Stage 1 - Technical Infrastructure</td>
<td>2,200</td>
</tr>
<tr>
<td>Stage 1 - FCC-ee Machine and Injector Complex</td>
<td>4,000</td>
</tr>
<tr>
<td>Stage 2 - Civil Engineering complement</td>
<td>600</td>
</tr>
<tr>
<td>Stage 2 - Technical Infrastructure adaptation</td>
<td>2,800</td>
</tr>
<tr>
<td>Stage 2 - FCC-hh Machine and Injector complex</td>
<td>13,600</td>
</tr>
<tr>
<td>TOTAL construction cost for integral FCC project</td>
<td>28,600</td>
</tr>
</tbody>
</table>
An FCC-hh detector

- Must be able to cope with:
  - very large dynamic range of signatures \((E = 20 \text{ GeV} - 20 \text{ TeV})\)
  - hostile environment \((1k \text{ pile-up and up to } 10^{18} \text{ cm}^{-2} \text{ MeV n eq fluence})\)

- Characteristics:
  - large acceptance (for low \(p_T\) physics)
  - extreme granularity (for high \(p_T\) and pile-up rejection)
  - timing capabilities
  - radiation hardness
Towards defining the FCChh detector

Physics constraints

- 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)
    • number of channels over large area can get too high

  → re-think reconstruction algorithms:
    • hard to reconstruct displaced vertices
    • exploit hit multiplicity discontinuity

Only 71% 5 TeV b-hadrons decay < 5th layer.
• displaced vertices
An FCC-hh detector that can do the job

**Tracker**
- $-6 < \eta < 6$ coverage
- pixel: $\sigma_{r\phi} \sim 10 \mu m$, $\sigma_{Z} \sim 15-30 \mu m$, $X/X_0(\text{layer}) \sim 0.5-1.5\%$
- outer: $\sigma_{r\phi} \sim 10 \mu m$, $\sigma_{Z} \sim 30-100 \mu m$, $X/X_0(\text{layer}) \sim 1.5-3\%$

**Calorimeters**
- ECAL: LArg, $30X_0$, $1.6 \lambda$, $r = 1.7-2.7$ m (barrel)
- HCAL: Fe/Sci, $9 \lambda$, $r = 2.8 - 4.8$ m (barrel)

**Magnet**
- central $R = 5$, $L = 10$ m, $B = 4$T
- forward $R = 3$ m, $L = 3$ m, $B = 4$T

**Muon spectrometer**
- Two stations separated by 1-2 m
- $50 \mu m$ pos., $70\mu rad$ angular
Tracker

- Binary readout
- 16 billions readout channels, x(3-10) phase II detectors
- Radiation hardness is an issue for innermost layers

- Tilted geometry with inclined modules:
  - minimize effect of Multiple scattering (low material)
  - helps with pattern recognition

Delphes

low $p_T$ muons $\rightarrow$ resolution dominated by MS

Dipole improves $\delta p_T/p_T$ by:

- $p_T = 10$ TeV/c
- $p_T = 1$ TeV/c
- $p_T = 100$ GeV/c
- $p_T = 10$ GeV/c
- $p_T = 5$ GeV/c
- $p_T = 1$ GeV/c

dashed lines show the
Calorimeters

- ECAL: LAr + Pb technology driven by radiation hardness
- HCAL:
  - Organic scintillator + Steel, R/O with WLS fiber + SiPM
  - LAr in the forward (Dose > 10 MGy)

- Design goals:
  - High longitudinal (7+10 layers) + transverse segmentation (x4 CMS and ATLAS)
  - Particle-flow compliant
  - standalone PU rejection

---

Full Sim

Delphes
Muons

- pT = 4 GeV muons enter the muon system
- pT = 5.5 GeV leave coil at 45 degrees

- Standalone muon measurement with angle of track exiting the coil
- Target muon resolution can be easily achieved with 50 μm position resolution (combining with tracker)
- Good standalone resolution below |η| < 2.5

σ_p/p = 10% @20 TeV

Delphes
High level objects

- **Jets**
  - hard to compare: no PFlow in full sim, but calo only OK (with simplistic clustering ECAL+HCAL clustering)

- **Heavy flavour tagging:**
  - no full-sim implementation
  - guided from LHC performance, but slightly improved motivated by more granular tracker and calorimeters
Cavern and MDI

- $L^* = 40\text{m}$ (as opposed $L^* = 23\text{ m}$ in LHC experiments)
- Last focusing quadrupoles are outside the cavern
- MDI is not a concern (as opposed to $e^+e^-$)
Radiation tolerance

Tracker:
first IB layer (2.5 cm): $\sim 6 \cdot 10^{17} \text{ cm}^{-2}$
HL-LHC rad. tolerance limit @ R=27 cm: $\sim 10^{16} \text{ cm}^{-2}$
external part: $\sim 5 \cdot 10^{15} \text{ cm}^{-2}$

Forward calorimetry:
maximum at $\sim 10^{18} \text{ cm}^{-2}$

- A hadron fluence $> 10^{16} \text{ cm}^{-2}$ is very challenging for silicon sensors
- This limit is reached already @ 27 cm from the beam pipe
- Dedicated R&D needed to push the limit of radiation hardness
Charged Particle fluence

- Barrel muon chambers: 300-500 Hz/cm²
- Fwd chambers: 25-250 kHz/cm²
- Endcap Muon Chambers: 10 kHz/cm²

Central tracker:
- first IB layer (2.5 cm): \( \sim 1.2 \times 10^{10} \text{ cm}^{-2}\text{s}^{-1} \)
- external part: \( 3 \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \)

\( \gamma \rightarrow ee \) created from thermalisation/neutron capture in calorimeters

Silicon sensors in the very forward region for muons?

ATLAS muon system HL-LHC rates (kHz/cm²):
- MDTs barrel: 0.28
- MDTs endcap: 0.42
- RPCs: 0.35
- TGCs: 2
- Micromegas und sTGCs: 9-10
Stray field and service cavern

No shielding: too expensive
Dipole vs. Solenoid

Dipole:
- Loose rotational symmetry
- Need compensation system for the hadron beam
- Better tracking performance however

| Table 7.2: Main characteristics of the central solenoid, a forward solenoid and a forward dipole magnet. |
|--------------------------------------------------|--------------------------------------------------|------------------|
| Unit             | Main solenoid | Forward solenoid | Forward dipole |
| Operating current | kA            | 30              | 30             | 16              |
| Stored energy    | GJ            | 12.5            | 0.43           | 0.20            |
| Self-inductance  | H             | 27.9            | 0.96           | 1.54            |
| Current density  | A/mm²         | 7.3             | 16.1           | 25.6            |
| Peak field on conductor | T             | 4.5             | 4.5            | 5.9             |
| Operating temperature | K             | 4.5             | 4.5            | 4.5             |
| Current sharing temp. | K             | 6.5             | 6.5            | 6.2             |
| Temperature margin | K             | 2.0             | 2.0            | 1.7             |
| Heat load cold mass | W             | 286             | 37             | 50              |
| Heat load thermal shield | W     | 5140            | 843            | 1500            |
| Cold mass        | t             | 1070            | 48             | 114             |
| Vacuum vessel    | t             | 875             | 32             | 48              |
| Conductor length | km            | 84              | 16             | 23              |

Figure 7.6: a) Cold mass for a central solenoid of 4 T with two forward solenoids and b) a central solenoid of 4 T and two forward dipole magnets with field integral of 4 Tm.

Figure 7.7: Longitudinal half-sections of the two versions of the magnet system. Magnetic fieldmap for a central solenoid of 4 T with a forward dipole (left) and a forward solenoid (right).
Total and residual ionizing dose

![Graphs showing total and residual ionizing dose.](image)
Figure 7.10: Material budget of the different sub-systems. The calorimetry provides $\geq 10.5 \lambda$ nuclear interaction lengths to maximise shower containment and the total detector material represents between 180 and 280 $X_0$ radiation lengths.
Pile-up rejection

With PU density = 8 mm\(^{-1}\) need \(\delta z_0 \sim 100 \ \mu m\) resolution in track longitudinal impact parameter.

\[ \rightarrow \text{at large angles this corresponds to beam-pipe contribution alone} \]

High resolution (~ 5-10 ps) timing information needed!!
Boosted b-tagging
Machine and detector requirements

**lumi & pile-up**

- LHC: 30 PU events/bc
- HL-LHC: 140 PU events/bc
- FCC-hh: 1000 PU events/bc

**Timing helps in identifying PU vertices**
Data rates and trigger

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}$ cross-section</td>
<td>mb</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>$b\bar{b}$ rate</td>
<td>MHz</td>
<td>5</td>
<td>25</td>
<td>250</td>
<td>750</td>
</tr>
<tr>
<td>$b\bar{b} p_T &gt; 30$ GeV/c cross-section</td>
<td>µb</td>
<td>1.6</td>
<td>1.6</td>
<td>4.3</td>
<td>28</td>
</tr>
<tr>
<td>$b\bar{b} p_T &gt; 30$ GeV/c rate</td>
<td>MHz</td>
<td>0.02</td>
<td>0.08</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Jets $p_T^{jet} &gt; 50$ GeV/c cross-section [341]</td>
<td>µb</td>
<td>21</td>
<td>21</td>
<td>56</td>
<td>300</td>
</tr>
<tr>
<td>Jets $p_T^{jet} &gt; 50$ GeV/c rate</td>
<td>MHz</td>
<td>0.2</td>
<td>1.1</td>
<td>14</td>
<td>90</td>
</tr>
</tbody>
</table>

Need more selectivity at Level 1 (full allocated Phasell bandwidth for single muon pt > 30 GeV)!

- **Phase II:**
  - ATLAS/CMS calorimeters/muons readout @40MHz and sent via optical fibres to Level 1 trigger outside the cavern to create L1 trigger decisions (25 Tb/s)
  - Full detector readout @1MHz (@40MHz ~ 200 Tb/s)

- **FCC-hh:**
  - At FCC-hh Calo+Muon would correspond to 250 Tb/s (seems feasible)
  - However full detector would correspond to 1-2 Pb/s
    - Seems hardly feasible (30 yrs from now)
  - More selectivity needed @L1 (4D hit information?)
Strategy for R & D

• High profile R&d program needs to be carried on to make this possible, (leverage HL-LHC efforts)

• Possible Directions:
  • Radiation hard silicon detectors
  • High precision timing
  • Low power, high speed links
  • Highly segmented calorimeters (3D imaging calorimeters)
  • Software, reconstruction algorithms (4D particle-flow, boosted object tagging)
  • Large scale muon systems
  • Magnets
  • Cryogenics

CERN has released a document
On plans for R&D as input to
European Strategy:

Strategic R&D Programme on
Technologies for Future Experiments
Photon resolution with PU

Large impact of in time PU on the noise term (out of the box with no improvements)!!

- severely degrades $m_{\gamma\gamma}$ resolution (improving clustering, not sliding windows may help)
- impacts Higgs self-coupling precision by $\delta K_\lambda \approx 1\%$
- some thought needed (tracking, timing information can help?)
Jet Performance with Full sim

- Excellent resolution up to $p_T = 10\,\text{TeV}$ !!
- Large impact of PU at low $p_T$ (as expected)

  - crucial for low mass di-jet resonances (again, such as $\text{HH} \rightarrow \text{bb}\gamma\gamma$)

  - Further motivation for Particle-flow

    $\rightarrow$ since charged PU contribution can be easily subtracted (Charged Hadron Subtraction)
Jet Pile-Up identification

- With 200-1000PU, will get huge amount of fake-jets from PU combinatorics
- need both longitudinal/lateral segmentation for PU identification
- Simplistic observables show possible handles, pessimistic.. (in reality tracking will help a lot)
Jet substructure

FCC-hh Simulation

\( p_T^{\text{jet}} > 500 \, \text{GeV} \)

Normalized event rate vs. \( m_{\text{jet}} \, [\text{GeV}] \)

\( \Delta R = \frac{2m}{p_T} \)

FCC-hh Simulation

Normalized event rate vs. \( \tau_{2,1} \)
Jet substructure

- Performance good up to 1 TeV, with Calorimeter standalone, and without B field!
- Far from having explored everything possible:
  - **Particle-Flow** tracks and B field (decrease local occupancy) will improve
  - **Machine Learning** techniques will help a lot (train on 3D shower image)
• **2m thick shielding wall to protect front of final focus system from collision debris**
Possible future colliders: FCC-hh

- Circumference = 100 km
- Need dipoles that generate B = 16 T

In its high luminosity phase, FCC-hh produces 1000 PU interactions per bunch crossing.
High Field Dipoles Magnets (16T)

- Nb-Ti not suited anymore (4-10T)
- Focus on Nb3Sn (also HLLHC)

Goal: $J_c = 1500 \text{ A/mm}^2$ @ 4.2 K

- High Temperature Superconductors (Bi-2212) are promising, but stress sensitive, also low current density (but constant)

Many challenges:
- Need margin $B \sim 20 \text{ T}$
- Conductor instabilities
- NbSn3 stress sensitivity …
- Cost?

How long? Manageable in ~ 15-20 yrs?
We often talk about “precise” SM measurements. What we actually aim at is “sensitive” tests of the Standard Model, 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:

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

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

\[
\delta O \sim \left( \frac{Q}{\Lambda} \right)^2 \quad \Rightarrow \text{kinematic reach probes large } \Lambda
\]

e.g. \( \delta O=15\% \) at \( Q=1 \text{ TeV} \Rightarrow \Lambda \sim 2.5 \text{ TeV} \)
Reach @100 TeV

$\mathcal{L}$ = integrated luminosity

$L = \text{parton luminosity}$

$L \sim \frac{1}{\tau^a}$, $\tau = x_1 x_2 = M^2 / s$

$L \sim \left(\frac{s}{M^2}\right)^a$

$\sigma \sim \frac{1}{M^2}$

# events = $\sigma \mathcal{L}$

$\sigma \approx \sigma \text{ (part) } L$

$\sigma \approx \left(\frac{s}{M^{2+2/a}}\right)^a$

Reach of collider at $\sqrt{s_1}$ vs $\sqrt{s_2}$:

$\frac{M_2}{M_1} \sim \left(\frac{s_2}{s_1}\right)^{1/2} \left[\left(\frac{s_1}{s_2}\right)\left(\frac{\mathcal{L}_1}{\mathcal{L}_2}\right)\right]^{1/(2a+1)}$

At high mass (high $x$), $a \gg 1$:

Mass reach goes up by factor 7 (roughly)

$L \sim \frac{1}{\tau^a}$

a$\approx$2

a$\approx$6
Ratio parton-luminosity

Indicates how rate of **given process** (e.g. single Higgs production) scales from 14 TeV to 100 TeV:

\[
\frac{\text{# events } (\sqrt{s} = 100 \text{ TeV})}{\text{# events } (\sqrt{s} = 14 \text{ TeV})} \approx \frac{L_1}{L_2} \approx \left( \frac{s_2}{s_1} \right)^a \approx \left( \frac{100}{14} \right)^{2a}
\]

![Graph showing PDF luminosities comparison between 100 TeV and 14 TeV](image)

- $a \approx 2$
- $a \approx 6$
Huge statistics allow for great potential of further exploration of SM particles at 100 TeV
\( HH \rightarrow bb\gamma\gamma \)

- 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 \(k_\lambda\)
- \(\delta k_\lambda / k_\lambda = 5\%-7\%\) (stat - stat+syst.) in this channel alone

\[ \delta k_\lambda / k_\lambda = 5\% \text{ doable by combining with other channels} \]
## Summary direct measurements

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC</th>
<th>FCC-ee</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta \Gamma_H / \Gamma_H$ (%)</td>
<td>SM</td>
<td>1.3</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{HZZ} / g_{HZZ}$ (%)</td>
<td>1.5</td>
<td>0.17</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{HWW} / g_{HWW}$ (%)</td>
<td>1.7</td>
<td>0.43</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{Hbb} / g_{Hbb}$ (%)</td>
<td>3.7</td>
<td>0.61</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{Hcc} / g_{Hcc}$ (%)</td>
<td>~70</td>
<td>1.21</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{Hgg} / g_{Hgg}$ (%)</td>
<td>2.5 (gg-&gt;H)</td>
<td>1.01</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)</td>
<td>1.9</td>
<td>0.74</td>
<td>tbd</td>
</tr>
<tr>
<td>$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)</td>
<td>4.3</td>
<td>9.0</td>
<td>0.65 (*)</td>
</tr>
<tr>
<td>$\delta g_{HYY} / g_{HYY}$ (%)</td>
<td>1.8</td>
<td>3.9</td>
<td>0.4 (*)</td>
</tr>
<tr>
<td>$\delta g_{Htt} / g_{Htt}$ (%)</td>
<td>3.4</td>
<td>–</td>
<td>0.95 (**)</td>
</tr>
<tr>
<td>$\delta g_{HZY} / g_{HZY}$ (%)</td>
<td>9.8</td>
<td>–</td>
<td>0.91 (*)</td>
</tr>
<tr>
<td>$\delta g_{HHH} / g_{HHH}$ (%)</td>
<td>50</td>
<td>~30 (indirect)</td>
<td>7</td>
</tr>
</tbody>
</table>

- **BR**$_{exo}$ (95%CL)  
  - **BR**$_{inv}$ < 2.5%  
  - < 1%  
  - **BR**$_{inv}$ < 0.025%

* From BR ratios wrt $B(H\rightarrow 4l)$ @ FCC-ee

** From $pp\rightarrow ttH / pp\rightarrow ttZ$, using $B(H\rightarrow bb)$ and ttZ EW coupling @ FCC-ee
Heavy resonances @ 100 TeV
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% 5 TeV b-hadrons decay < 5th layer.
- displaced vertices
Disappearing Tracks

- Observed relic density of Dark Matter Higgsino-like: 1 TeV, Wino-like: 3 TeV
- Mass degeneracy: wino 170 MeV, Higgsino 350 MeV
- Wino/Higgsino LSP meta-stable chargino, $cT = 6\text{cm(}\text{wino)}$, 7 mm(higgsino)
- Disappearing tracks analysis shows discovery reach beyond upper limits of MDM
- In a similar way FCC-hh can explore conclusively EW charged WIMP models, (low multiplets)
Heavy resonances @ 100 TeV

- $M = 1$ TeV Higgsino can be discovered
- $M = 3$ TeV Wino can be discovered
The nature of the EW phase transition

Strong \(1^{\text{st}}\) order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

**Strong** \(1^{\text{st}}\) order phase transition \(\Rightarrow \langle \Phi_C \rangle > T_C\)

**In the SM this requires** \(m_H \leq 80\) GeV, else transition is a smooth crossover.

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

- Probe higher-order terms of the Higgs potential (self couplings)
- 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