Physics prospects of future hadron colliders

Michelangelo L. Mangano
Theory Department,
CERN, Geneva
pp @ 14 TeV, 3ab$^{-1}$
100km tunnel

- $e^+e^- @ 91, 160, 240, 365$ GeV
- $pp @ 100$ TeV
- $e_{60 GeV} p_{50 TeV} @ 3.5$ TeV

LHC tunnel: HE-LHC

- $pp @ 27$ TeV, 15ab$^{-1}$

Lecture 2 by B. Ferrando

link to CDR

pp @ 14 TeV, 3ab$^{-1}$

Approved 2026-37
pp @ 14 TeV, 3ab$^{-1}$

100km tunnel

- $e^+e^- @ 91, 160, 240, 365$ GeV
- **pp @ 100 TeV**
- $e_{60\text{GeV}} p_{50\text{TeV}} @ 3.5$ TeV

LHC tunnel: HE-LHC

- pp @ 27 TeV, 15ab$^{-1}$

Lecture 2 by B. Ferrando

---

 Approved 2026-37

---

CEPC

100km tunnel

- $e^+e^- @ 91, 240$ GeV (but possibly 160 & 350)
- Future possible pp @ ~70 TeV and $e_{60\text{GeV}} p_{35\text{TeV}}$
Key question for the future developments of HEP: Why don’t we see the new physics we expected to be present around the TeV scale?
Key question for the future developments of HEP:
Why don’t we see the new physics we expected to be present around the TeV scale?

- Is the mass scale beyond the LHC reach?
- Is the mass scale within LHC’s reach, but final states are elusive to the direct search?
Key question for the future developments of HEP: Why don’t we see the new physics we expected to be present around the TeV scale?

- Is the mass scale beyond the LHC reach?

- Is the mass scale within LHC’s reach, but final states are elusive to the direct search?

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities.
**Key question for the future developments of HEP:** Why don’t we see the new physics we expected to be present around the TeV scale?

- Is the mass scale beyond the LHC reach?

- Is the mass scale within LHC’s reach, but final states are elusive to the direct search?

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities.

Readiness to address both scenarios is the best hedge for the field:

- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*
Remark

the discussion of the future in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can **guarantee discoveries** beyond the SM, and **answers** to the big questions of the field
What do we want from a future collider?

The physics potential (the “case”) of a future facility for HEP should be weighed against criteria such as:
What do we want from a future collider?

The physics potential (the “case”) of a future facility for HEP should be weighed against criteria such as:

- **Guaranteed deliverables:**
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible precision and sensitivity
What do we want from a future collider?

The physics potential (the “case”) of a future facility for HEP should be weighed against criteria such as:

- **Guaranteed deliverables:**
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible precision and sensitivity

- **Exploration potential:**
  - exploit both direct (large $Q^2$) and indirect (precision) probes
  - enhanced mass reach for direct exploration
    - E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector
What do we want from a future collider?

The physics potential (the “case”) of a future facility for HEP should be weighed against criteria such as:

- **Guaranteed deliverables:**
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible precision and sensitivity

- **Exploration potential:**
  - exploit both direct (large $Q^2$) and indirect (precision) probes
  - enhanced mass reach for direct exploration
    - E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector

- **Provide firm Yes/No answers** to questions like:
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - could the cosmological EW phase transition have been 1st order?
  - could baryogenesis have taken place during the EW phase transition?
  - could neutrino masses have their origin at the TeV scale?
  - …
Guaranteed deliverables:

what more will we need to know about the Higgs after the HL-LHC? will it not get “boring” to keep studying the Higgs and the top?
Who ordered that?

\[ V(H) = -\mu^2 |H|^2 + \lambda |H|^4 \]
Who ordered that?

We must learn to appreciate the depth and the value of this question, which is set to define the future of collider physics.
Electromagnetic vs Higgs dynamics

\[ V(r) = \frac{q_1 \times q_2}{r^1} \]
Electromagnetic vs Higgs dynamics

\[ V(r) = + \frac{q_1 \times q_2}{r^1} \]

quantized, in units of fixed charge
Electromagnetic vs Higgs dynamics

\[ V(r) = \frac{q_1 \times q_2}{r^1} \]

- Sign fixed by photon spin
- Power determined by gauge invariance/charge conservation/Gauss theorem
- Quantized, in units of fixed charge
Electromagnetic vs Higgs dynamics

\[ V(r) = \mathbf{q}_1 \times \mathbf{q}_2 \]

- Sign fixed by photon spin
- Power determined by gauge invariance/charge conservation/Gauss theorem
- Quantized, in units of fixed charge

\[ V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4 \]
Electromagnetic vs Higgs dynamics

\[ V(r) = q_1 x q_2 \]

- Sign fixed by photon spin
- Power determined by gauge invariance/charge conservation/Gauss theorem

\[ V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4 \]

- Both sign and value totally arbitrary
- \( >0 \) to ensure stability, but otherwise arbitrary
Electromagnetic vs Higgs dynamics

$q_1 \times q_2$

$V(r) = \frac{q_1 \times q_2}{r}$

quantized, in units of fixed charge

sign fixed by photon spin

power determined by gauge invariance/charge conservation/Gauss theorem

$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$

any function of $|H|^2$ would be ok wrt known symmetries

both sign and value totally arbitrary

$>0$ to ensure stability, but otherwise arbitrary
a historical example: superconductivity
a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.
a historical example: superconductivity

• The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

• For superconductivity, this came later, with the identification of e⁻e⁻ Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don’t know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and we must look beyond.
examples of possible scenarios

- **BCS-like**: the Higgs is a composite object

- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2 + g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus $m_H$ and $\lambda$) determined by the parameters of SUSY breaking

- ...
Hierarchy problem and naturalness!!

Lecture 2 by M. Mc Cullough
The hierarchy problem, and the search for a \textit{natural} explanation of the separation between the Higgs and Planck scales, provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.
• The hierarchy problem, and the search for a natural explanation of the separation between the Higgs and Planck scales, provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.

• Lack of experimental evidence, so far, for a straightforward answer to naturalness (eg SUSY), forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties.
The hierarchy problem, and the search for a natural explanation of the separation between the Higgs and Planck scales, provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.

Lack of experimental evidence, so far, for a straightforward answer to naturalness (eg SUSY), forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties.

We often ask “is the Higgs like in SM?” .... The right way to set the issue is rather, more humbly, “what is the Higgs?” ...
• The hierarchy problem, and the search for a natural explanation of the separation between the Higgs and Planck scales, provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.

• Lack of experimental evidence, so far, for a straightforward answer to naturalness (e.g., SUSY), forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties.

• We often ask “is the Higgs like in SM?” … The right way to set the issue is rather, more humbly, “what is the Higgs?” …

  ● in this perspective, even innocent questions like whether the Higgs gives mass also to 1\textsuperscript{st} and 2\textsuperscript{nd} generation fermions call for experimental verification.
• The hierarchy problem, and the search for a natural explanation of the separation between the Higgs and Planck scales, provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.

• Lack of experimental evidence, so far, for a straightforward answer to naturalness (eg SUSY), forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties.

• We often ask “is the Higgs like in SM?” …. The right way to set the issue is rather, more humbly, “what is the Higgs?” …

  • in this perspective, even innocent questions like whether the Higgs gives mass also to 1st and 2nd generation fermions call for experimental verification.

⇒ all this justifies the focus on the program of precision Higgs physics measurements
• The hierarchy problem, and the search for a *natural* explanation of the separation between the Higgs and Planck scales, provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.

• Lack of experimental evidence, so far, for a straightforward answer to naturalness (eg SUSY), forces us to review our biases, and to **take a closer look even at the most basic assumptions about Higgs properties**

• We often ask “is the Higgs like in SM?” ….The right way to set the issue is rather, more humbly, **“what is the Higgs?”** …

  • in this perspective, even innocent questions like whether the Higgs gives mass also to 1st and 2nd generation fermions call for experimental verification.

=> all this justifies the focus on the program of precision Higgs physics measurements

=> colliders are the only facilities that make this possible
Other important open issues on the Higgs sector
Other important open issues on the Higgs sector

• Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^\pm, A^0, H^{\pm\pm}, \ldots, EW$-singlets, \ldots) ?
  • Do all SM families get their mass from the \textcolor{red}{same} Higgs field?
  • Do $I_3=1/2$ fermions (up-type quarks) get their mass from the \textcolor{red}{same} Higgs field as $I_3=-1/2$ fermions (down-type quarks and charged leptons)?
  • Do Higgs couplings conserve flavour? $H \rightarrow \mu \tau$? $H \rightarrow e \tau$? $t \rightarrow H c$?
Other important open issues on the Higgs sector

• Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^\pm$, $A^0$, $H^{\pm\pm}$, ..., EW-singlets, ....)?
  • Do all SM families get their mass from the same Higgs field?
  • Do $l_3=1/2$ fermions (up-type quarks) get their mass from the same Higgs field as $l_3=-1/2$ fermions (down-type quarks and charged leptons)?
  • Do Higgs couplings conserve flavour? $H \rightarrow \mu \tau$? $H \rightarrow e\tau$? $t \rightarrow Hc$?

• Is there a deep reason for the apparent metastability of the Higgs vacuum? => see L. Reina lecture 3
Other important open issues on the Higgs sector

• Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^\pm, A^0, H^{\pm\pm}, \ldots, EW$-singlets, \ldots) ?
  • Do all SM families get their mass from the same Higgs field?
  • Do $I_3=1/2$ fermions (up-type quarks) get their mass from the same Higgs field as $I_3=-1/2$ fermions (down-type quarks and charged leptons)?
  • Do Higgs couplings conserve flavour? $H \rightarrow \mu \tau$? $H \rightarrow e \tau$? $t \rightarrow Hc$?

• Is there a deep reason for the apparent metastability of the Higgs vacuum? => see L. Reina lecture 3

• Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?
Other important open issues on the Higgs sector

• Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^\pm$, $A^0$, $H^{\pm\pm}$, ... , EW-singlets, ...)?
  • Do all SM families get their mass from the same Higgs field?
  • Do $l_3=1/2$ fermions (up-type quarks) get their mass from the same Higgs field as $l_3=-1/2$ fermions (down-type quarks and charged leptons)?
  • Do Higgs couplings conserve flavour? $H\rightarrow\mu\tau$? $H\rightarrow e\tau$? $t\rightarrow Hc$?

• Is there a deep reason for the apparent metastability of the Higgs vacuum? => see L. Reina lecture 3

• Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?

• What happens at the EW phase transition (PT) during the Big Bang?
  • what’s the order of the phase transition?
  • are the conditions realized to allow EW baryogenesis?
The nature of the EW phase transition

1\textsuperscript{st} order

\[ \langle h \rangle = 0 \rightarrow \langle h \rangle = h(T) \text{ Discontinuous} \]

2\textsuperscript{nd} order or cross-over

\[ \langle h \rangle = 0 \rightarrow \langle h \rangle = h(T) \text{ Continuous} \]
The nature of the EW phase transition

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 $O(\text{TeV})$**, must modify the Higgs potential to make this possible.

**Strong** $1^{\text{st}}$ 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.**
The nature of the EW phase transition

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

\textbf{Strong} \textit{1st} order phase transition \(\Rightarrow\) \(\langle \Phi_C \rangle > T_C\)

\textbf{In the SM this requires} \(m_H \lesssim 80\) GeV, else transition is a smooth crossover.

Since \(m_H = 125\) GeV, \textbf{new physics}, coupling to the Higgs and effective at \textbf{scales} \(O(\text{TeV})\), 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
1st Order EWPT has profound implications for cosmology

\[ \langle \text{Higgs} \rangle = v(T) \quad \langle \text{Higgs} \rangle = 0 \]

Primordial Gravitational Waves

Primordial Magnetic Field

Primordial Black Holes

Matter

Excess

see LISA science paper: 1512.06239

Andrew Long @ FCC physics Workshop, Jan 2018
https://indico.cern.ch/event/618254
Higgs couplings, beyond the HL-LHC: the $e^+e^-$ phase

<table>
<thead>
<tr>
<th>Collider</th>
<th>HL-LHC update</th>
<th>ILC$_{250}$</th>
<th>CLIC$_{380}$</th>
<th>LEP3$_{240}$</th>
<th>CEPC$_{250}$</th>
<th>FCC-ee$_{240+365}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi (ab$^{-1}$)</td>
<td>3</td>
<td>2</td>
<td>0.5</td>
<td>3</td>
<td>5</td>
<td>5$<em>{240}$ +1.5$</em>{365}$ + HL-LHC</td>
</tr>
<tr>
<td>Years</td>
<td>25</td>
<td>15</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>3 +4</td>
</tr>
<tr>
<td>$\delta \Gamma _H/\Gamma _H$ (%)</td>
<td>50</td>
<td>3.6</td>
<td>6.3</td>
<td>3.6</td>
<td>2.6</td>
<td>2.7 1.3 1.1</td>
</tr>
<tr>
<td>$\delta g_{hZZ}/g_{hZZ}$ (%)</td>
<td>1.5</td>
<td>0.3</td>
<td>0.40</td>
<td>0.32</td>
<td>0.25</td>
<td>0.20 0.17 0.16</td>
</tr>
<tr>
<td>$\delta g_{hWW}/g_{hWW}$ (%)</td>
<td>1.7</td>
<td>1.7</td>
<td>0.8</td>
<td>1.7</td>
<td>1.2</td>
<td>1.3 0.43 0.40</td>
</tr>
<tr>
<td>$\delta g_{Hbb}/g_{Hbb}$ (%)</td>
<td>3.7</td>
<td>1.7</td>
<td>1.3</td>
<td>1.8</td>
<td>1.3</td>
<td>1.3 0.61 0.56</td>
</tr>
<tr>
<td>$\delta g_{Hcc}/g_{Hcc}$ (%)</td>
<td>SM</td>
<td>2.3</td>
<td>4.1</td>
<td>2.3</td>
<td>1.8</td>
<td>1.7 1.21 1.18</td>
</tr>
<tr>
<td>$\delta g_{Hgg}/g_{Hgg}$ (%)</td>
<td>2.5</td>
<td>2.2</td>
<td>2.1</td>
<td>2.1</td>
<td>1.4</td>
<td>1.6 1.01 0.90</td>
</tr>
<tr>
<td>$\delta g_{Htt}/g_{Htt}$ (%)</td>
<td>1.9</td>
<td>1.9</td>
<td>2.7</td>
<td>1.9</td>
<td>1.4</td>
<td>1.4 0.74 0.67</td>
</tr>
<tr>
<td>$\delta g_{HWW}/g_{HWW}$ (%)</td>
<td>4.3</td>
<td>14.1</td>
<td>n.a.</td>
<td>12</td>
<td>6.2</td>
<td>10.1 9.0 3.8</td>
</tr>
<tr>
<td>$\delta g_{HYY}/g_{HYY}$ (%)</td>
<td>1.8</td>
<td>6.4</td>
<td>n.a.</td>
<td>6.1</td>
<td>4.7</td>
<td>4.8 3.9 1.3</td>
</tr>
<tr>
<td>$\delta g_{Htt}/g_{Htt}$ (%)</td>
<td>3.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>– 3.1</td>
</tr>
<tr>
<td>BR$_{EXO}$ (%)</td>
<td>SM</td>
<td>&lt; 1.7</td>
<td>&lt; 3.0</td>
<td>&lt; 1.6</td>
<td>&lt; 1.2</td>
<td>&lt; 1.2 &lt; 1.0 &lt; 1.0</td>
</tr>
</tbody>
</table>
Higgs couplings, beyond the HL-LHC: 
the e⁺e⁻ phase

<table>
<thead>
<tr>
<th>Collider</th>
<th>HL-LHC update</th>
<th>ILC_{250}</th>
<th>CLIC_{380}</th>
<th>LEP3_{240}</th>
<th>CEPC_{250}</th>
<th>FCC-ee_{240+365}</th>
<th>( +) HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi (ab^{-1})</td>
<td>3</td>
<td>2</td>
<td>0.5</td>
<td>3</td>
<td>5</td>
<td>5_{240}</td>
<td>+1.5_{365}</td>
</tr>
<tr>
<td>Years</td>
<td>25</td>
<td>15</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>3</td>
<td>+4</td>
</tr>
<tr>
<td>( \delta \Gamma_H / \Gamma_H ) (%)</td>
<td>50</td>
<td>3.6</td>
<td>6.3</td>
<td>3.6</td>
<td>2.6</td>
<td>2.7</td>
<td>1.3</td>
</tr>
<tr>
<td>( \delta g_{\text{Hzz}} / g_{\text{Hzz}} ) (%)</td>
<td>1.5</td>
<td>0.3</td>
<td>0.40</td>
<td>0.32</td>
<td>0.25</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>( \delta g_{\text{HWW}} / g_{\text{HWW}} ) (%)</td>
<td>1.7</td>
<td>1.7</td>
<td>0.8</td>
<td>1.7</td>
<td>1.2</td>
<td>1.3</td>
<td>0.43</td>
</tr>
<tr>
<td>( \delta g_{\text{Hbb}} / g_{\text{Hbb}} ) (%)</td>
<td>3.7</td>
<td>1.7</td>
<td>1.3</td>
<td>1.8</td>
<td>1.3</td>
<td>1.3</td>
<td>0.61</td>
</tr>
<tr>
<td>( \delta g_{\text{Hcc}} / g_{\text{Hcc}} ) (%)</td>
<td>SM</td>
<td>2.3</td>
<td>4.1</td>
<td>2.3</td>
<td>1.8</td>
<td>1.7</td>
<td>1.21</td>
</tr>
<tr>
<td>( \delta g_{\text{Hgg}} / g_{\text{Hgg}} ) (%)</td>
<td>2.5</td>
<td>2.2</td>
<td>2.1</td>
<td>2.1</td>
<td>1.4</td>
<td>1.6</td>
<td>1.01</td>
</tr>
<tr>
<td>( \delta g_{\text{Htt}} / g_{\text{Htt}} ) (%)</td>
<td>1.9</td>
<td>1.9</td>
<td>2.7</td>
<td>1.9</td>
<td>1.4</td>
<td>1.4</td>
<td>0.74</td>
</tr>
<tr>
<td>( \delta g_{\text{H\mu\mu}} / g_{\text{H\mu\mu}} ) (%)</td>
<td>4.3</td>
<td>14.1</td>
<td>n.a.</td>
<td>12</td>
<td>6.2</td>
<td>10.1</td>
<td>9.0</td>
</tr>
<tr>
<td>( \delta g_{\text{HYY}} / g_{\text{HYY}} ) (%)</td>
<td>1.8</td>
<td>6.4</td>
<td>n.a.</td>
<td>6.1</td>
<td>4.7</td>
<td>4.8</td>
<td>3.9</td>
</tr>
<tr>
<td>( \delta g_{\text{Htt}} / g_{\text{Htt}} ) (%)</td>
<td>3.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>BR_{EXO} (%)</td>
<td>SM</td>
<td>&lt; 1.7</td>
<td>&lt; 3.0</td>
<td>&lt; 1.6</td>
<td>&lt; 1.2</td>
<td>&lt; 1.2</td>
<td>&lt; 1.0</td>
</tr>
</tbody>
</table>

Table 1: Relative statistical uncertainty on the Higgs boson couplings and total decay width, as expected from the FCC-ee data, and compared to those from HL-LHC and other e⁺e⁻ colliders exploring the 240-to-380 GeV centre-of-mass energy range. All numbers indicate 68% CL intervals, except for the last line which gives the 95% CL sensitivity on the “exotic” branching fraction, accounting for final states that cannot be tagged as SM decays. The FCC-ee accuracies are subdivided in three categories: the first sub-column give the results of the model-independent fit expected with 5 ab^{-1} at 240 GeV, the second sub-column in bold – directly comparable to the other collider fits – includes the additional 1.5 ab^{-1} at \( \sqrt{s} = 365 \) GeV, and the last sub-column shows the result of the combined fit with HL-LHC. The fit to the HL-LHC projections alone (first column) requires two additional assumptions to be made: here, the branching ratios into c\bar{c} and into exotic particles are set to their SM values.

1. To significantly improve the expected HL-LHC results, future facilities must push Higgs couplings’ precision to the sub-% level.

2. Event rates higher than what ee colliders can provide are needed to reach sub-% measurements of couplings such as $H\gamma\gamma$, $H\mu\mu$, $HZ\gamma$, $Htt$. 
The unique contributions of a 100 TeV pp collider to Higgs physics

- **Huge Higgs production rates:**
  - access (very) rare decay modes
  - push to %-level Higgs self-coupling measurement
  - new opportunities to reduce syst uncertainties (TH & EXP) and push precision

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

- **High energy reach**
  - direct probes of BSM extensions of Higgs sector
    - SUSY Higgses
    - Higgs decays of heavy resonances
    - Higgs probes of the nature of EW phase transition
    - …
### SM Higgs: event rates in pp@100 TeV

<table>
<thead>
<tr>
<th></th>
<th>gg→H</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>ttH</th>
<th>HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_{100})</td>
<td>24 x 10⁹</td>
<td>2.1 x 10⁹</td>
<td>4.6 x 10⁸</td>
<td>3.3 x 10⁸</td>
<td>9.6 x 10⁸</td>
<td>3.6 x 10⁷</td>
</tr>
<tr>
<td>(N_{100}/N_{14})</td>
<td>180</td>
<td>170</td>
<td>100</td>
<td>110</td>
<td>530</td>
<td>390</td>
</tr>
</tbody>
</table>

\[N_{100} = \sigma_{100\,\text{TeV}} \times 30 \, \text{ab}^{-1}\]

\[N_{14} = \sigma_{14\,\text{TeV}} \times 3 \, \text{ab}^{-1}\]
Hierarchy of production channels changes at large $p_T(H)$:

- $\sigma(t\bar{t}H) > \sigma(gg\rightarrow H)$ above 800 GeV
- $\sigma(VBF) > \sigma(gg\rightarrow H)$ above 1800 GeV
At LHC, S/B in the H→γγ channel is O( few % )
At FCC, for $p_T(H) > 300$ GeV, S/B~1
Potentially accurate probe of the H pt spectrum up to large pt

<table>
<thead>
<tr>
<th>$p_T,_{min}$ (GeV)</th>
<th>$\delta_{stat}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.2%</td>
</tr>
<tr>
<td>400</td>
<td>0.5%</td>
</tr>
<tr>
<td>600</td>
<td>1%</td>
</tr>
<tr>
<td>1600</td>
<td>10%</td>
</tr>
</tbody>
</table>
\[ gg \rightarrow H \rightarrow ZZ^* \rightarrow 4l \text{ at large } p_T \]

\[ N = \sigma(p_T(4l) > p_{T,\text{min}}) \times 20 \text{ ab}^{-1} \]

\[ |M(4l)| < 125 \text{ GeV}, \quad |p_{T,l}| > 10 \text{ GeV}, \quad |\eta| < 2.5 \]

- Solid: \( H \rightarrow Z^*(*)Z^*(*) \rightarrow 4l \)
- Dashes: \( q\bar{q}/qg \rightarrow Z^*(*)Z^*(*) + X \)

\( l = e, \mu \)

- \( p_T, \text{min} \) (GeV)

<table>
<thead>
<tr>
<th>( p_T, \text{min} ) (GeV)</th>
<th>( \delta_{\text{stat}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.3%</td>
</tr>
<tr>
<td>300</td>
<td>1%</td>
</tr>
<tr>
<td>1000</td>
<td>10%</td>
</tr>
</tbody>
</table>

- \( S/B \sim 1 \) for inclusive production at LHC
- Practically bg-free at large \( p_T \) at 100 TeV, maintaining large rates
Importance of standalone precise “ratios-of-BRs" measurements:

- independent of $\alpha_s$, $m_b$, $m_c$, $\Gamma_{\text{inv}}$ systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

1. $\frac{\text{BR}(H \rightarrow \gamma\gamma)}{\text{BR}(H \rightarrow ZZ^*)}$
   - loop-level to tree-level

2. $\frac{\text{BR}(H \rightarrow \mu\mu)}{\text{BR}(H \rightarrow ZZ^*)}$
   - 2nd gen’n Yukawa to gauge coupling

3. $\frac{\text{BR}(H \rightarrow \gamma\gamma)}{\text{BR}(H \rightarrow Z\gamma)}$
   - different EW charges in the loops of the two procs

4. $\frac{\text{BR}(H \rightarrow \text{inv})}{\text{BR}(H \rightarrow \gamma\gamma)}$
   - tree-level neutral to loop-level charged
### Higgs couplings after FCC-ee / hh

<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>~10 (indirect)</td>
<td>0.95 (**)</td>
</tr>
<tr>
<td>$\delta g_{HZY} / g_{HZY}$ (%)</td>
<td>9.8</td>
<td>–</td>
<td>0.9 (*)</td>
</tr>
<tr>
<td>$\delta g_{HHH} / g_{HHH}$ (%)</td>
<td>50</td>
<td>~44 (indirect)</td>
<td>6.5</td>
</tr>
</tbody>
</table>

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<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 $B(H\rightarrow 4\text{lept})$ @ FCC-ee

** From $pp\rightarrow ttH / pp\rightarrow ttZ$, using $B(H\rightarrow bb)$ and $ttZ$ EW coupling @ FCC-ee
Higgs self-coupling, $gg \rightarrow HH$

From the detector performance studies:

<table>
<thead>
<tr>
<th>Process</th>
<th>$\delta k_\lambda$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bb\gamma\gamma$</td>
<td>6.5</td>
</tr>
<tr>
<td>$bbZZ[\rightarrow 4l]$</td>
<td>14</td>
</tr>
<tr>
<td>$bbWW[\rightarrow 2jl\nu]$</td>
<td>40</td>
</tr>
<tr>
<td>$4b+j$</td>
<td>30</td>
</tr>
<tr>
<td>$2b2\tau+j$</td>
<td>8</td>
</tr>
</tbody>
</table>

Pheno-level studies:

$bb\gamma\gamma$

$bbZZ[\rightarrow 4l]$

$bbWW[\rightarrow 2jl\nu]$

$4b+j$

$2b2\tau+j$

Figure 10.4: Expected precision on the Higgs self-coupling modifier $k_\lambda$ with no systematic uncertainties (only statistical), 1% signal uncertainty, 1% signal uncertainty together with 1% uncertainty on the Higgs backgrounds (left) and assuming respectively $\times 1$, $\times 2$, $\times 0.5$ background yields (right).
Example of precision targets: constraints on models with 1\textsuperscript{st} order phase transition

\[
V(H, S) = -\mu^2 \left( H\dagger H \right) + \lambda \left( H\dagger H \right)^2 + \frac{a_1}{2} \left( H\dagger H \right) S
+ \frac{a_2}{2} \left( H\dagger H \right) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4.
\]
**Example of precision targets:**

**constraints on models with 1st order phase transition**

\[ V(H, S) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S \]

\[ + \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4. \]

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.
**Example of precision targets:** constraints on models with 1st order phase transition

\[ V(H, S) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S \]
\[ + \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4. \]

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

Direct detection of extra Higgs states at FCC-hh

Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

\[ h_2 \rightarrow h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\pi) \]
\[ (h_2 \sim S, \quad h_1 \sim H) \]
Precision vs sensitivity
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.
Precision vs sensitivity

• 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 …
High-$Q^2$ observables: precision vs dynamic reach

\[ L = L_{SM} + \frac{1}{\Lambda^2} \sum_k O_k + \cdots \]

\[ O = | \langle f | L | i \rangle |^2 = O_{SM} \left[ 1 + O(\mu^2/\Lambda^2) + \cdots \right] \]
High-$Q^2$ observables: precision vs dynamic reach

\[ L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots \]

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

For $H$ decays, or inclusive production, $\mu \sim O(v,m_H)$

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

e.g. $\delta O=1\% \Rightarrow \Lambda \sim 2.5$ TeV
High-$Q^2$ observables: precision vs dynamic reach

\[ L = L_{SM} + \frac{1}{\Lambda^2} \sum_k O_k + \cdots \]

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

For H decays, or inclusive production, $\mu \sim O(v,m_H)$

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

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

For H production off-shell or with large momentum transfer $Q$, $\mu \sim O(Q)$

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

\[ \text{e.g. } \delta O=10\% \text{ at } Q=1.5 \text{ TeV} \Rightarrow \Lambda \sim 5 \text{ TeV} \]
High-$Q^2$ observables: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k O_k + \cdots$$

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

For H decays, or inclusive production, $\mu \sim O(v,m_H)$

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

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

For H production off-shell or with large momentum transfer $Q$, $\mu \sim O(Q)$

$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2 \Rightarrow \text{kinematic reach probes large } \Lambda \text{ even if precision is "low"}$$

\(\text{e.g. } \delta O=10\% \text{ at } Q=1.5 \text{ TeV } \Rightarrow \Lambda \sim 5 \text{ TeV}\)

Complementarity between precise measurements at ee collider and large-$Q$ studies at 100 TeV
Examples

\[ \delta \text{BR}(H \rightarrow gg) \]

\[ \delta \text{BR}(H \rightarrow WW^*) \]

\[ L_{D=6} = \frac{i g c_W}{2 \Lambda^2} (H^\dagger \sigma^a D^\mu H) D^\nu V^a_{\mu\nu} \]

\[ \frac{\sigma}{\sigma_{SM}} \sim \left(1 + c_W \frac{\hat{s}}{\Lambda^2} \right)^2 \]
Example: high mass $VV \rightarrow HH$

$$A(V_LV_L \rightarrow HH) \sim \frac{s}{v^2}(c_{2V} - c_V^2) \cdot \text{where} \begin{cases} c_V = \frac{g_{HVV}}{g_{SM}^{HVV}} \\ c_{2V} = \frac{g_{HHV}^{SM}}{g_{HHVV}} \end{cases} \Rightarrow (c_{2V} - c_V^2)_{SM} = 0$$
**WLWL scattering**

![Graphical representation of WLWL scattering](image)

**large mww**

![FCC-hh Simulation (Delphes)](image)

---

**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 $WLWL \rightarrow HH$ 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>

\[
\kappa_W = \frac{g_{HWW}}{g_{SM}^{HWW}}
\]
Direct discovery reach: the power of 100 TeV
Only a selection of the available searches is shown. Many of the plotted mass points are simplified models, c.f., ref. for the assumptions made.
s-channel resonances

FCC-hh Simulation (Delphes), $\sqrt{s} = 100$ TeV

- $Q^* \rightarrow jj$
- $Z'_{TC2} \rightarrow t\bar{t}$
- $Z'_{SSM} \rightarrow t\bar{t}$
- $G_{RS} \rightarrow W^+W^-$
- $Z'_{SSM} \rightarrow l^+l^-$
- $Z'_{SSM} \rightarrow \tau^+\tau^-$

FCC-hh reach ~ 6 x HL-LHC reach
Global EFT fits to EW and H observables at FCC-ee

Constraints on the coefficients of various EFT op’s from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

100 TeV is the appropriate CoM energy to directly search for new physics appearing indirectly through precision EW and H measurements at the future ee collider

=> see L. Reina lecture 3
Early phenomenology studies

SUSY reach at 100 TeV

New detector performance studies
WIMP DM theoretical constraints

See lecture 1 by M. Mc Cullough

For particles held in equilibrium by pair creation and annihilation processes, \((\chi \chi \leftrightarrow \text{SM})\)

\[
\Omega_{\text{DM}} h^2 \sim \frac{10^9 \text{GeV}^{-1}}{M_{\text{pl}}} \frac{1}{\langle \sigma v \rangle}
\]
**WIMP DM theoretical constraints**

*See lecture 1 by M. Mc Cullough*

For particles held in equilibrium by pair creation and annihilation processes, \((\chi \chi \leftrightarrow \text{SM})\)

\[
\Omega_{\text{DM}} h^2 \sim \frac{10^9 \text{GeV}^{-1}}{M_{\text{pl}}} \frac{1}{\langle \sigma v \rangle}
\]

For a particle annihilating through processes which do not involve any larger mass scales:

\[
\langle \sigma v \rangle \sim \frac{g_{\text{eff}}^4}{M_{\text{DM}}^2}
\]

\[
\Omega_{\text{DM}} h^2 \sim 0.12 \times \left( \frac{M_{\text{DM}}}{2 \text{ TeV}} \right)^2 \left( \frac{0.3}{g_{\text{eff}}} \right)^4
\]
WIMP DM theoretical constraints

For particles held in equilibrium by pair creation and annihilation processes, $(\chi \chi \leftrightarrow \text{SM})$

$$\Omega_{\text{DM}} h^2 \sim \frac{10^9 \text{GeV}^{-1}}{M_{\text{pl}}} \frac{1}{\langle \sigma v \rangle}$$

For a particle annihilating through processes which do not involve any larger mass scales:

$$\langle \sigma v \rangle \sim \frac{g_{\text{eff}}^4}{M_{\text{DM}}^2}$$

$$\Omega_{\text{DM}} h^2 \sim 0.12 \times \left( \frac{M_{\text{DM}}}{2 \text{ TeV}} \right)^2 \left( \frac{0.3}{g_{\text{eff}}} \right)^4$$

$$\Omega_{\text{wimp}} h^2 \lesssim 0.12$$

$$M_{\text{wimp}} \lesssim 2 \text{ TeV} \left( \frac{g}{0.3} \right)^2$$

See lecture 1 by M. Mc Cullough
DM reach at 100 TeV

Early phenomenology studies

Collider Limits

- wino
- higgsino
- mixed (\tilde{B}/\tilde{H})
- mixed (\tilde{B}/\tilde{W})
- gluino coan.
- stop coan.
- squark coan.

\( m_{\tilde{\chi}} \) [TeV]
New detector performance studies

Disappearing charged track analyses
(at ~full pileup)

=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

$M_{\text{wimp}} \lesssim 2 \text{ TeV} \left( \frac{g}{0.3} \right)^2$
MSSM Higgs @ 100 TeV

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

FCC-ee + FCC-hh, project timeline

1. Project preparation & administrative processes
2. Permissions
3. Funding strategy
4. Funding and in-kind contribution agreements
5. Geological investigations, infrastructure detailed design and tendering preparation
6. Tunnel, site and technical infrastructure construction
7. Superconducting wire and magnet R&D
8. FCC-ee accelerator R&D and technical design
9. FCC-ee detector technical design
10. Setup of international experiment collaborations, detector R&D and concept development
11. FCC-ee detector construction, installation, commissioning
12. FCC-ee accelerator construction, installation, commissioning
13. FCC-ee accelerator R&D and technical design
14. FCC-ee detector R&D, technical design
15. FCC-ee detector construction, installation, commissioning
16. FCC-hh accelerator R&D and technical design
17. FCC-hh detector R&D, technical design
18. FCC-hh detector construction, installation, commissioning
19. FCC-ee dismantling, CE & infrastructure adaptations FCC-hh
20. SC wire and 16 T magnet R&D, model magnets, prototypes, pre-series
21. 16 T dipole magnet series production
22. 15 years operation
23. ~25 years operation
24. Update Permissions
25. Funding and in-kind contribution agreements
Table 5: Summary of capital cost to implement the integral FCC programme (FCC-ee followed by FCC-hh).

<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><strong>TOTAL construction cost for integral FCC project</strong></td>
<td><strong>28,600</strong></td>
</tr>
</tbody>
</table>
Final remarks
Final remarks

• The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.
The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.

- The combination of a versatile high-luminosity $e^+e^-$ circular collider, with a follow-up pp collider in the 100 TeV range, appears like the ideal facility for the post-LHC era.
Final remarks

• The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.

• The combination of a versatile high-luminosity e^+e^- circular collider, with a follow-up pp collider in the 100 TeV range, appears like the ideal facility for the post-LHC era

• *complementary and synergetic precision studies of EW, Higgs and top properties*
Final remarks

• The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.

• The combination of a versatile high-luminosity $e^+e^−$ circular collider, with a follow-up pp collider in the 100 TeV range, appears like the ideal facility for the post-LHC era

  • *complementary and synergetic precision studies of EW, Higgs and top properties*
  • *energy reach to allow direct discoveries at the mass scales possibly revealed by the precision measurements*
Additional material on physics at HE-LHC

For details see


(1) extension of mass reach for discovery: s-channel resonances
(1) EW-ino DM searches

Examples of goals in the Higgs sector:
(a) improve the sensitivity to the Higgs self-coupling
(b) reduce to the few percent level all major Higgs couplings
(c) improve the sensitivity to possible invisible Higgs decays
(d) measure the charm Yukawa coupling

<table>
<thead>
<tr>
<th></th>
<th>$gg \to H$</th>
<th>WH</th>
<th>ZH</th>
<th>$ttH$</th>
<th>HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{27}$</td>
<td>$2.2 \times 10^9$</td>
<td>$5.4 \times 10^7$</td>
<td>$3.7 \times 10^7$</td>
<td>$4 \times 10^7$</td>
<td>$2.1 \times 10^6$</td>
</tr>
<tr>
<td>$N_{27}/N_{14}$</td>
<td>13</td>
<td>12</td>
<td>13</td>
<td>23</td>
<td>19</td>
</tr>
</tbody>
</table>

$N_{27} = \sigma(27 \text{ TeV}) \times 15 \text{ ab}^{-1}$

$N_{14} = \sigma(14 \text{ TeV}) \times 3 \text{ ab}^{-1}$
Higgs self-coupling at HE-LHC vs HL-LHC

**HL-LHC:** $\lambda/\lambda_{SM} \sim 1 \pm 0.5$ (68%CL)

**HE-LHC:** $\lambda/\lambda_{SM} \sim 1 \pm 0.15$ (68%CL)

**IV** Exploration at 27 TeV of LHC discoveries: characterization of Z’ models within reach of LHC observation

NB: uncertainty bars reflect very conservative syst assumptions

Colours: different Z’ models, leading to observation at HL-LHC in Z’->dilepton decay for m(Z’) = 6 TeV

HE-LHC: the challenges

- 16T Nb$_3$Sn magnets: more challenging than for FCC-hh, due to reduced space in the tunnel (requires dedicated R&D)

- SPS upgrade, to SC technology, to allow injection at 0.9-1.3 TeV
- Full replacement and strengthening of all infrastructure on the surface and underground cryogenics
- Significant civil engineering work both on the surface and in the tunnel (new SPS transfer lines, new caverns for cryogenics, 2 new shafts, …)
- Overhaul/full replacement of detectors (radiation damage after HL-LHC, limited lifetime of key systems like magnets, use of new technologies, …)
- …
HE-LHC, project timeline/cost

Figure 7: Overview of implementation timeline for the HE-LHC project starting in 2020. Numbers in the top row indicate the year. Physics operation would start in the mid 2040ies.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Cost in MCHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collider</td>
<td>5,000</td>
</tr>
<tr>
<td>Injector complex</td>
<td>1,100</td>
</tr>
<tr>
<td>Technical infrastructure</td>
<td>800</td>
</tr>
<tr>
<td>Civil Engineering</td>
<td>300</td>
</tr>
<tr>
<td><strong>TOTAL cost</strong></td>
<td><strong>7,200</strong></td>
</tr>
</tbody>
</table>

Table 2: Summary of capital cost for implementation of the HE-LHC project.