Theoretical studies of future (hadron) colliders

Michelangelo L. Mangano
CERN, Theory Department

See also in the parallel sessions:

Gauthier Durieux: Physics of future lepton colliders
Giancarlo Ferrera: Physics of future hadron colliders
Steinar Stapnes: Status of ILC and CLIC projects
Rogelio Tomas Garcia: Status of FCC study

FCC-hh: “Physics at 100 TeV”, Report, 5 chapters:
• SM processes, arXiv:1607.01831
• Higgs and EWSB studies, arXiv:1606.09408
• BSM phenomena, arXiv:1606.00947
• Heavy Ions at the FCC, arXiv:1605.01389
• Physics opportunities with the FCC injectors, arXiv:1706.07667
Higgs .... what else?
Higgs .... what else?

Who ordered that?

\[ V(H) = -\mu^2|H|^2 + \lambda|H|^4 \]
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.
what’s ahead?

- HEP has two priorities:
  - explore the physics of electroweak symmetry breaking:
    - experimentally, via the measurement of Higgs properties, Higgs interactions and selfinteractions, couplings of gauge bosons, flavour phenomena, etc
    - theoretically, to understand the origin of the Higgs potential, the nature of the hierarchy problem and identify possible natural solutions (to be subjected to exptl test)
  - explore the origin of known departures from the SM (DM, neutrino masses, baryon asymmetry of the universe)
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Planning the future builds on the belief that these two directions are deeply intertwined
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?
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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
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  - **mass reach enhanced** by factor $\sim E / 14 \text{ TeV}$ (will be 5–7 at 100 TeV, depending on integrated luminosity)
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• **Provide firm Yes/No answers** to questions like:
  • is the SM dynamics all there is at the TeV scale?
  • is there a TeV-scale solution to the hierarchy problem?
  • is DM a thermal WIMP?
  • was the cosmological EW phase transition 1st order? Cross over? ??
  • could baryogenesis take place during the EW phase transition?
Higgs properties,
some sample studies
# Higgs couplings @ FCC-ee

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**SM Higgs: event rates at 100 TeV**

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<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 $10^9$</td>
<td>2.1 x $10^9$</td>
<td>4.6 x $10^8$</td>
<td>3.3 x $10^8$</td>
<td>9.6 x $10^8$</td>
<td>3.6 x $10^7$</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>
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$N_{100} = \sigma_{100\text{ TeV}} \times 30 \text{ ab}^{-1}$

$N_{14} = \sigma_{14\text{ TeV}} \times 3 \text{ ab}^{-1}$
The uniqueness of

**FCC-hh contributions 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 $p_T^H$, $m(H+X)$, ...):**
  - 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 (strong 1$^{st}$ order? crossover?)
  - ...

...
**H at large $p_T$**

- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg\rightarrow H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg\rightarrow H)$ above 1800 GeV
At LHC, S/B in the $H \rightarrow \gamma\gamma$ channel is $O(\text{few \%})$.

At FCC, for $p_T(H) > 300$ GeV, $S/B \sim 1$.

Potentially accurate probe of the $H$ pt spectrum up to large $p_T$.

<table>
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<th>$p_T,_{\text{min}}$ (GeV)</th>
<th>$\delta_{\text{stat}}$</th>
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<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>
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Delphes-based projections

All signal and background samples have been generated via the following chain (using the FCCSW):


- **MG5aMC@NLO + Pythia8**
  - LO (MLM) matched samples (up to 1/2/3 jets) and global K-factor applied to account for N^{2/3}LO corrections
  - full list of signal prod. modes simulated (ggH with finite m_{top})
- Delphes-3.4.2 with baseline FCC-hh detector

Consider the following categories of uncertainties:

- $\delta_{\text{stat}} = \text{statistical}$
- $\delta_{\text{prod}} = \text{production + luminosity systematics}$
- $\delta_{\text{eff}} (i) (p_T) = \text{object reconstruction (trigger+isolation +identification) systematics}$
- $\delta_B = 0, \text{background (assume to have } \infty \text{ statistics from control regions)}$

Assume (un-)correlated uncertainties for (different) same final state objects

Following scenarios are considered:

- $\delta_{\text{stat}} \rightarrow \text{stat. only (I)}$
- $\delta_{\text{stat}}, \delta_{\text{eff}} \rightarrow \text{stat. + eff. unc. (II)}$
- $\delta_{\text{stat}}, \delta_{\text{eff}}, \delta_{\text{prod}} = 1\% \rightarrow \text{stat. + eff. unc. + prod (III)}$
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could be seen as syst in the normalization of production*lumi wrt standard candles such as \( pp \rightarrow Z \rightarrow ee \)
\( \delta \frac{\text{BR}(H \rightarrow \mu\mu)}{\text{BR}(H \rightarrow 4\mu)} \) (%)

\( \delta \frac{\text{BR}(H \rightarrow \gamma\gamma)}{\text{BR}(H \rightarrow 2\mu 2e)} \) (%)

\( \delta \frac{\text{BR}(H \rightarrow \gamma\gamma)}{\text{BR}(H \rightarrow 2\mu)} \) (%)

Normalize to BR(4l) from FCC-ee at 1% level \( \Rightarrow \) absolute sub-% for couplings

M. Selvaggi
BR(H→inv) in H+X production at large p_T(H)

Constrain bg pt spectrum from Z→νν to the % level using NNLO QCD/EW to relate to measured Z→ee, W and γ spectra

SM sensitivity with 1ab⁻¹, can reach few x 10⁻⁴ with 30ab⁻¹
Table 1.2: Target precision for the parameters relative to the measurement of various Higgs couplings, the Higgs self-coupling $\lambda$, Higgs branching ratios $B$ and ratios thereof. Notice that lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings.

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<td>$\mu = \sigma(H) \times B(H \to \gamma\gamma)$</td>
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Study for $B(H \to Z\gamma)$ in progress
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first probe of the Higgs potential beyond the 2-point function

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Study for $B(H \to Z\gamma)$ in progress

sensitive to possible Higgs-to-DM decays
Competitive with the best direct detection experiments

Impact on DM bounds

Higgs invisible bound

BR (\(H \rightarrow \text{inv.}\)) < 0.0001

Taking optimistic bound

Higgs invisible of \(10^{-4}\) corresponds to \(g_{\text{SM}}\) from \(10^{-3}\) to \(10^{-2}\)
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High-$Q^2$ aspects

- 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 …
Higgs as a BSM probe: precision vs dynamic reach

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

\[ O = | \langle f | L | i \rangle |^2 = O_{SM} \left[ 1 + O(\mu^2/\Lambda^2) + \cdots \right] \]
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For H decays, or inclusive production, \( \mu \sim O(v,m_H) \)

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

e.g. \( \delta O=1\% \Rightarrow \Lambda \sim 2.5 \text{ TeV} \)
Higgs as a BSM probe: precision vs dynamic reach

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

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

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

\[ \delta O \sim \left( \frac{Q}{\Lambda} \right)^2 \]

\[ \Rightarrow \text{kinematic reach probes large } \Lambda \text{ even if precision is “low”} \]

\[ \text{e.g. } \delta O=10\% \text{ at } Q=1.5 \text{ TeV} \Rightarrow \Lambda \sim 5 \text{ TeV} \]
Higgs as a BSM probe: precision vs dynamic reach

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

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

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, \( \mu \sim O(Q) \)

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

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

Complementarity between super-precise measurements at ee collider and large-Q studies at 100 TeV
Examples: direct discovery reach
Resonances: SSM $Z'$

C. Helsens & M. Selvaggi + Summer students
Rachel Smith UIUC and Ine Arts UA
SUSY reach at 100 TeV

95% CL Limits
- 14 TeV, 0.3 ab⁻¹
- 14 TeV, 3 ab⁻¹
- 5 σ Discovery
- 100 TeV, 3 ab⁻¹
- 100 TeV, 30 ab⁻¹

Mass scale [TeV]
DM reach at 100 TeV

$M_{\text{WIMP}} \leq 1.8 \text{ TeV} \left( \frac{g^2}{0.3} \right)$

possibility to find (or rule out) thermal WIMP DM candidates
MSSM Higgs @ 100 TeV

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

HE-LHC physics potential: domains to be evaluated

(1) extension of the LHC direct search for new particles (approximately doubling its mass reach);

(2) the Higgs self-coupling: establishing firm evidence for the structure of the symmetry-breaking Higgs potential;

(3) increased precision in the measurements made by the LHC, and the consequent increased sensitivity to new physics (indirectly to high mass scales, and, directly, to elusive final states such as dark matter);

(4) exploration of future LHC discoveries, confirmation of preliminary signs of discovery from the LHC, or the search for the underlying origin of new phenomena revealed indirectly (e.g. the flavour anomalies under discussion nowadays) or in experiments other than the LHC ones (e.g. dark matter or neutrino experiments).
(1) extension of mass reach for discovery: generic results

Figure 1.1: Estimate of the system mass (e.g. $m_{Z'}$ or $2m_{\tilde{g}}$) that can be probed in searches for new particles at HE-LHC, given an established system mass reach at HL-LHC.

(1) extension of mass reach for discovery: “natural” supersymmetry examples

Figure 1.2: Discovery reach at the HE-LHC for gluinos and stops in various, compared to the HL-LHC reach and to the expectations of a several classes of natural supersymmetric models.


For recent 27 TeV projections of DM WIMP 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→H</th>
<th>WH</th>
<th>ZH</th>
<th>ttH</th>
<th>HH</th>
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<td>(N_{27})</td>
<td>2.2x10^8</td>
<td>5.4x10^7</td>
<td>3.7x10^7</td>
<td>4x10^7</td>
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<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>

\[N_{27} = \sigma(27 \text{ TeV}) \times 15 \text{ ab}^{-1}\]  \[N_{14} = \sigma(14 \text{ TeV}) \times 3 \text{ ab}^{-1}\]
First results on Higgs selfcouplings measurement:


\[ \frac{\lambda}{\lambda_{SM}} = 1 \pm 0.3 \text{ at } 95\% \text{CL} \quad (1 \pm 0.15 \text{ at } 68\% \text{CL}) \]

(compare to \(-0.2 < \frac{\lambda}{\lambda_{SM}} < 2.6 \) at HL-LHC)


For couplings like \( H\gamma\gamma, H\Z\gamma, H\mu\mu, Htt, \ldots \), plan to repeat studies presented at 100 TeV
(IV) Exploration at 27 TeV of LHC discoveries: generic results

\[ \frac{\sigma(27 \text{ TeV}) \times 15 \text{ab}^{-1}}{\sigma(14 \text{ TeV}) \times 3 \text{ab}^{-1}} \]

PDF4LHC15 PDF, \( Q^2 = M^2 \)

Solid: \( gg \rightarrow M \)
Dashes: \( qg \rightarrow M \)
Dotdash: \( qq \rightarrow M \)
(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

T. Rizzo, work in progress.

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

27 or 100? $\sqrt{S}$ evolution of LHC discovery scenarios

\[
\frac{\sigma(pp\to X)[\sqrt{S}]}{\sigma(pp\to X)[14 \text{ TeV}]}
\]

- \(gg\to X\)
  - \(m_X(\text{TeV}) = 6, 4, 2, 1, 0.5\)
- \(qq\to X\)
  - \(m_X(\text{TeV}) = 6, 4, 2, 1, 0.5\)
Possible questions/options

• If $m_X \sim 6\,\text{TeV}$ in the $gg$ channel, rate grows $\times 200$ @28\,TeV:
  • Do we wait to go to $pp@100\,\text{TeV}$, or fast-track 28\,TeV in the LHC tunnel?
  • Do we need 100\,TeV, or 50 is enough ($\frac{\sigma_{100}}{\sigma_{14}} \sim 4 \cdot 10^4$, $\frac{\sigma_{50}}{\sigma_{14}} \sim 4 \cdot 10^3$)?
  • .... and the answers may depend on whether we expect partners of $X$ at masses $\gtrsim 2m_X$ ($\Rightarrow$ 28\,TeV would be insufficient ....)

• If $m_X \sim 0.5\,\text{TeV}$ in the $qqbar$ channel, rate grows $\times 10$ @100\,TeV:
  • Do we go to 100\,TeV, or push by $\times 10$ $\int L$ at LHC?
  • Do we build CLIC?

• etc.etc.
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.
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• As a possible complement to the mature ILC and CLIC projects, plans are underway to define the possible continuation of this programme after the LHC, with the same goals of thoroughness, precision and breadth that inspired the LEP/LHC era
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• As a possible complement to the mature ILC and CLIC projects, plans are underway to define the possible continuation of this programme after the LHC, with the same goals of thoroughness, precision and breadth that inspired the LEP/LHC era.

• The physics case of a 100 TeV collider is very clear as a long-term goal for the field, simply because no other proposed or foreseeable project can have direct sensitivity to such large mass scales.
Final remarks

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• The physics case of a 100 TeV collider is very clear as a long-term goal for the field, simply because no other proposed or foreseeable project can have direct sensitivity to such large mass scales.

• Nevertheless, the precise route followed to get there must take account of the fuller picture, to emerge from the LHC as well as other current and future experiments in areas ranging from flavour physics to dark matter searches.
Workshop on the physics of HL-LHC, and perspectives at HE-LHC

18-20 June 2018
CERN

https://indico.cern.ch/event/686494/

Next general mtg: June 18-20, CERN,  https://indico.cern.ch/event/686494/

Workshop twiki pages:  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop

To join the mailing list, click here
Technical Schedule for each of the 3 Options

- **16 T magnets**
- **FCC-hh**
- **FCC-ee**
- **HE-LHC**

Schedule constrained by 16 T magnets & CE
→ earliest possible physics starting dates
- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)

M. Benedikt