Higgs measurements at Future Circular Colliders

SUSY 2016
Melbourne, July 3-8, 2016

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Which Machine(s)?

**Hadrons**
- large mass reach ⇒ exploration?
- $S/B \sim 10^{-10}$ (w/o trigger)
- $S/B \sim 0.1$ (w/ trigger)
- requires multiple detectors (w/ optimized design)
- only pdf access to $\sqrt{s}$
- ⇒ couplings to quarks and gluons

**Leptons**
- $S/B \sim 1$ ⇒ measurement?
- polarized beams (handle to choose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇒ EW couplings

**Circular**
- $\sqrt{s}$ limited by synchrotron radiation
- higher luminosity
- several interaction points
- precise E-beam measurement
  \(O(0.1\text{MeV})\) @ FCC-ee via resonant depolarization

**Linear**
- easier to upgrade in energy
- easier to polarize beams
- large beamstrahlung
- greener: less power consumption
**HL-LHC** (2023-2035)

14 TeV - 3/ab

**LHC / HL-LHC Plan**

<table>
<thead>
<tr>
<th>Year</th>
<th>7 TeV</th>
<th>8 TeV</th>
<th>13-14 TeV</th>
<th>14 TeV</th>
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<tbody>
<tr>
<td>2011</td>
<td></td>
<td></td>
<td>13-14 TeV</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td></td>
<td>13-14 TeV</td>
<td></td>
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<td>2013</td>
<td></td>
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<td>13-14 TeV</td>
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<tr>
<td>2014</td>
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<td>2017</td>
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<td>13-14 TeV</td>
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<td>2018</td>
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<td>2019</td>
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<td></td>
<td>13-14 TeV</td>
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<td>2020</td>
<td></td>
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<td>13-14 TeV</td>
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<tr>
<td>2021</td>
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<td>13-14 TeV</td>
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<td>2022</td>
<td></td>
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<td>13-14 TeV</td>
<td></td>
</tr>
<tr>
<td>2023</td>
<td></td>
<td></td>
<td>13-14 TeV</td>
<td></td>
</tr>
<tr>
<td>2024</td>
<td></td>
<td></td>
<td>13-14 TeV</td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td></td>
<td></td>
<td>13-14 TeV</td>
<td></td>
</tr>
<tr>
<td>2035</td>
<td></td>
<td></td>
<td>13-14 TeV</td>
<td></td>
</tr>
</tbody>
</table>

**Higgs bosons at vs=14 TeV**

- **HL-LHC, 3000 fb⁻¹**: 170M
- **VBF (all decays)**: 13M
- **ttH (all decays)**: 1.8M
- **H→Zγ**: 230k
- **H→μμ**: 37k
- **HH (all)**: 121k

<table>
<thead>
<tr>
<th>Energy (fb⁻¹)</th>
<th>Experiment</th>
<th>K_Y</th>
<th>K_W</th>
<th>K_Z</th>
<th>K_R</th>
<th>K_b</th>
<th>K_t</th>
<th>K_τ</th>
<th>K_{Z_Y}</th>
<th>K_μ</th>
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<tbody>
<tr>
<td>300 fb⁻¹</td>
<td>ATLAS</td>
<td>[9,9]</td>
<td>[9,9]</td>
<td>[8,8]</td>
<td>[11,14]</td>
<td>[22,23]</td>
<td>[20,22]</td>
<td>[13,14]</td>
<td>[24,24]</td>
<td>[21,21]</td>
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<td>300 fb⁻¹</td>
<td>CMS</td>
<td>[5,7]</td>
<td>[4,6]</td>
<td>[4,6]</td>
<td>[6,8]</td>
<td>[10,13]</td>
<td>[14,15]</td>
<td>[6,8]</td>
<td>[41,41]</td>
<td>[23,23]</td>
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<tr>
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<td>ATLAS</td>
<td>[4,5]</td>
<td>[4,5]</td>
<td>[4,4]</td>
<td>[5,9]</td>
<td>[10,12]</td>
<td>[8,11]</td>
<td>[9,10]</td>
<td>[14,14]</td>
<td>[7,8]</td>
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<tr>
<td>30000 fb⁻¹</td>
<td>CMS</td>
<td>[2,5]</td>
<td>[2,5]</td>
<td>[2,4]</td>
<td>[3,5]</td>
<td>[4,7]</td>
<td>[7,10]</td>
<td>[2,5]</td>
<td>[10,12]</td>
<td>[8,8]</td>
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</tbody>
</table>
**FCC-ee** \((x=\text{post HL-LHC} - x+20)/CepC\) \(??-??\)

240/350/(500) - 10/ab
### Future circular colliders

- CEPC+SppC
- Where (if in China): Qin-Huang-Dao, China.
- Higgs factory: CEPC
- pp Collider: SppC
- CERN
- Higgs factory: FCC-ee
- pp Collider: FCC-hh

This talk: will focus more on ee, with some results from pp.

Thursday, April 23, 2015

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**FCC-ee (x=post HL-LHC - x+20)/CEPC (??-??)**

240/350/(500) - 10/ab

<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-ee</th>
<th>CEPC</th>
<th>LEP2</th>
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<tbody>
<tr>
<td>energy/beam [GeV]</td>
<td>45</td>
<td>120</td>
<td>175</td>
</tr>
<tr>
<td>bunches/beam</td>
<td>13000-60000</td>
<td>500-1400</td>
<td>51-98</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>1450</td>
<td>30</td>
<td>6.6</td>
</tr>
<tr>
<td>luminosity/IP \times 10^{34} cm^{-2}s^{-1}</td>
<td>21-280</td>
<td>5-11</td>
<td>1.5-2.6</td>
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<tr>
<td>energy loss/turn [GeV]</td>
<td>0.03</td>
<td>1.67</td>
<td>7.55</td>
</tr>
<tr>
<td>synchrotron power [MW]</td>
<td>100</td>
<td>103</td>
<td>22</td>
</tr>
<tr>
<td>RF voltage [GV]</td>
<td>0.2-2.5</td>
<td>3.6-5.5</td>
<td>11</td>
</tr>
</tbody>
</table>

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@FCC-ee

- $10^6 H$
- $10^{12} Z$ possible upgrade to $10^{13} Z$ (line-shape, mass & width, probe rare (FCNC) decays)
- $10^8 W$ (mass)
- $3 \times 10^{10}$ tau/muon pairs
- $2 \times 10^{11}$ b/c quarks $\rightarrow 20'000 B_s \rightarrow \tau^+ \tau^-$
- TLEP@340/500: $10^6$ top pairs (pole mass, probe FCNC decays, top Yukawa)

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Christophe Grojean

Higgs @ FCC

Melbourne, July 4, 2016
**FCC-ee** $(x=\text{post HL-LHC} - x+20)/\text{CepC}$ (?-??)

240/350/(500) - 10/ab

- CDR and cost review due in 2018

The FCC and CepC are essentially equivalent proposals with different emphasis; FCC – hadrons via e+e-, CepC – e+e- then hadrons

Mike Harrison, SPC meeting Sept. 2015

Christophe Grojean

Higgs @ FCC
**μ collider aka project X** (TBD: ?-?)

126/1'000/10'000 GeV - O(1)/ab

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**Physics Frontiers**

- Intense and cold muon beams ⇔ unique physics reach
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

- Opportunities
  - s-channel production of scalar objects
  - Strong coupling to particles like the Higgs
  - Reduced synchrotron radiation ⇔ multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects suppressed at IP
  - BUT accelerator complex/detector must be able to handle the impacts of μ decay

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**Colliders**

- High intensity beams required for a long-baseline Neutrino Factory are readily provided in conjunction with a Muon Collider Front End
  - Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations

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**Collider Synergies**

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M. Palmer, CERN '15

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Christophe Grojean

Higgs @ FCC

Melbourne, July 4, 2016
FCC-hh/SppC (TBC: 2035-2060)
80/100 TeV - 30/ab

Future circular colliders

CEPC+SppC
• Where(if in China):
– For example, Qin-Huang-Dao China.
Higgs factory:  CEPC
pp Collider: SppC

CERN
Higgs factory:  FCC-ee
pp Collider: FCC-hh

This talk: will focus more on ee, with some results from pp.

Thursday, April 23, 15

80/100 TeV   -   30/ab
Preliminary Conceptual Design Reports from:
http://cepc.ihep.ac.cn/preCDR/volume.html
- Vol 2: Accelerator (ready)
- Vol 1: Physics and detectors (any day soon ....)
FCC-hh/SppC (TBC: 2035-2060)  
80/100 TeV - 30/ab

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>SppC</th>
<th>LHC</th>
<th>HL LHC</th>
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<tr>
<td>collision energy cms [TeV]</td>
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<td>71.2</td>
<td>14</td>
<td></td>
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<tr>
<td>dipole field [T]</td>
<td>16</td>
<td>20</td>
<td>8.3</td>
<td></td>
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<tr>
<td># IP</td>
<td>2 main &amp; 2</td>
<td>2</td>
<td>2 main &amp; 2</td>
<td></td>
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<tr>
<td>bunch intensity [10^{11}]</td>
<td>1</td>
<td>1 (0.2)</td>
<td>2</td>
<td>1.1</td>
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<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25 (5)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>luminosity/Ip [10^{34} cm^{-2}s^{-1}]</td>
<td>5</td>
<td>25</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>events/bx</td>
<td>170</td>
<td>850 (170)</td>
<td>400</td>
<td>27</td>
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<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>6.6</td>
<td>0.36</td>
<td>0.7</td>
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<tr>
<td>synchr. rad. [W/m/apert.]</td>
<td>30</td>
<td>58</td>
<td>0.2</td>
<td>0.35</td>
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Higgs as a particular object to study

Preamble

- W/Z discovered in ’83. Still discussing today how to improve the measurement of their properties! Hadron colliders played, are playing and will continue playing a key role in this game
  - reasonable to expect the same will be true for the Higgs 30-40 yrs after 2012
- Precision measurements of Higgs properties are the guaranteed deliverable of any future energy-frontier facility
  - set performance benchmarks, and allow cross-comparisons among facilities
  - little we know of physics at the TeV scale!! (see the 750 GeV excitement)
- Higgs will soon become an analysis tool, if not a background, like W/Z and like the top quark
  - need to learn how to deal with and optimize the exploitation of large samples
- pp@100 TeV vs $e^+e^-$ (LC or CC): complementarity, synergy and more ....

M. Mangano, KUST’16
Higgs programme at future colliders

more energy + more luminosity = more Higgses

@ 100 TeV

<table>
<thead>
<tr>
<th>Process</th>
<th>#σ</th>
<th>#N / 10 ab⁻¹</th>
</tr>
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<tbody>
<tr>
<td>gg→H</td>
<td>740 pb</td>
<td>7.4 G</td>
</tr>
<tr>
<td>VBF</td>
<td>82 pb</td>
<td>0.8 G</td>
</tr>
<tr>
<td>WH</td>
<td>16 pb</td>
<td>160 M</td>
</tr>
<tr>
<td>ZH</td>
<td>11 pb</td>
<td>110 M</td>
</tr>
<tr>
<td>ttH</td>
<td>38 pb</td>
<td>380 M</td>
</tr>
<tr>
<td>gg→HH</td>
<td>1.4 pb</td>
<td>14 M</td>
</tr>
</tbody>
</table>

Statistical precision:
- O(100 - 500) better w.r.t Run I
- O(10 - 20) better w.r.t HL-LHC

- better measurements of Higgs properties: mass, width
- precision measurements of Higgs couplings
- access to rare decay modes
- access at rare production modes/kinematical distributions
- discovery of extended Higgs sectors

# of Higgses in 3 ab⁻¹

100 TeV > 2 billion
33 TeV > 500 million
14 TeV > 150 million

In comparison, O(million)
Higgs at Higgs factories

M. Mangano, HXSWG ‘15
Which opportunities for new measurements and probes of Higgs properties are made possible by these new channels?

<table>
<thead>
<tr>
<th></th>
<th>σ(14 TeV)</th>
<th>R(33)</th>
<th>R(40)</th>
<th>R(60)</th>
<th>R(80)</th>
<th>R(100)</th>
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<td>ggH</td>
<td>50.4 pb</td>
<td>3.5</td>
<td>4.6</td>
<td>7.8</td>
<td>11.2</td>
<td>14.7</td>
</tr>
<tr>
<td>VBF</td>
<td>4.40 pb</td>
<td>3.8</td>
<td>5.2</td>
<td>9.3</td>
<td>13.6</td>
<td>18.6</td>
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<tr>
<td>WH</td>
<td>1.63 pb</td>
<td>2.9</td>
<td>3.6</td>
<td>5.7</td>
<td>7.7</td>
<td>9.7</td>
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<td>4.2</td>
<td>6.8</td>
<td>9.6</td>
<td>12.5</td>
</tr>
<tr>
<td>ttH</td>
<td>0.62 pb</td>
<td>7.3</td>
<td>11</td>
<td>24</td>
<td>41</td>
<td>61</td>
</tr>
<tr>
<td>HH</td>
<td>33.8 fb</td>
<td>6.1</td>
<td>8.8</td>
<td>18</td>
<td>29</td>
<td>42</td>
</tr>
</tbody>
</table>

Relative importance of production modes modified in favor of VBF and ttH

FCC-hh = H+X factory

Higgs-diboson associated production

Higgs-pair associated production

(Plots from P. Torrielli and MLM, CERN'14)
Rare Higgs production/decay

FCC-hh =
probe extreme kinematic regimes

Dotted horizontal lines in the left panel correspond to the production of to the indicated final states, emerges as the most abundant source of large.

The ability to use this high BR decay extends considerably the accessible event rates in excess of tector performance issues, The key purpose is to show what is in principle possible and postpone more.

Can probe Higgs mixing via to ~<10% precision
determine Higgs couplings

In this Section we shall elaborate in some more detail on these ideas, One could organize the with 3 ab

Integrated Higgs transverse momentum rates for various production channels with 2(ab

Table 19: this category, has been shown \[112\] to be promising in this respect already at the high-luminosity LHC, in particular the vertices \[110, 111\]. In particular the vertices \[109\] for a recent analysis. Rates for these slightly reduced at 100 TeV with respect to 8 TeV, as shown explicitly in the left panel of figure

At 100 TeV the situation will improve considerably: the NLO cross section for the main irreducible production come to be more important than 20 over a broad range of

The only way to probe higgs mixing e.g. \[h \rightarrow Z \rightarrow 4l\] or even \[h \rightarrow jets\]

Christophe Grojean

Melbourne, July 4, 2016
ee colliders vs. hh colliders

~~ significant steps in precision study of Higgs properties ~~

(1) Higgs kinematic parameters: $m_H$ and $\Gamma_H$

→ reduce parametric uncertainties in $\sigma$ and BR
→ control the fate of EW vacuum within the SM
→ constrain new physics models (e.g. MSSM)

(2) Precise and model-independent access to Higgs couplings

→ 1% level
→ identification of correlation patterns among deviations
→ indirect test of extended Higgs sectors/composite nature
→ ultimate test of naturalness

(3) Access to decays modes that are background dominated @ LHC

→ $b\bar{b}/c\bar{c}/g\bar{g}$
→ exotic decay modes (portal models of Dark Matter)

(4) Constraints on Higgs flavor violating couplings

→ shed light on the origin of fermion masses and flavors
Lepton colliders provide a unique opportunity to make model independent measurements of Higgs couplings via the measurement of $\sigma(e^+e^- \to ZH)$

$Z$ is reconstructed independently of Higgs decay

4-momentum of the Higgs obtained from

$$E_{rec} = \sqrt{s} - E_Z \quad \vec{p}_{rec} = -\vec{p}_Z$$

Obtain a model independent measurement of $g_{zz}$ of $\sim 1\%$

Higgs mass from recoil mass
Higgs couplings to electrons (unique to FCC-ee)

- Higgs-$e^\pm$ Yukawa $g_{Hee}$ unobservable via decay: $\text{BR}(H\to e^+e^-)\approx 5.3\cdot10^{-9}$
- Resonant s-channel production considered so far only for $\mu\mu$ collider ($\sigma_{\mu\mu\to H} \sim 70$ pb).

\[
\sigma(e^+e^-\to H) = \frac{4\pi\Gamma_H^2\text{Br}(H\to e^+e^-)}{(s-M_H^2)^2 + \Gamma_H^2M_H^4} \approx 1.6 \text{ fb}
\]

Analysis of 7 Higgs decay channels:
- $L_{\text{int}} = 10 \text{ ab}^{-1}$, $S=0.65$:
  - $\text{BR}(\text{Hee}) < 4.6\times\text{BR}_{\text{SM}} (3\sigma)$
  - $g_{\text{hee}} < 2.2 \times g_{\text{Hee,SM}} (3\sigma)$

Operators with $\gamma$:
- already severely constrained by $e$ and $q$ EDMs
  - McKeen, Pospelov, Ritz ’12

Operators with top:
- already severely constrained by $e$ and $q$ EDMs
  - Brod, Haisch, Zupan ’13

\[\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \leq 10^{-4}\]
\[\Lambda_{\text{CP}} > 25 \text{ TeV}\]
\[\delta\tilde{g}_{htt} \leq 0.01\]
\[\Lambda_{\text{CP}} > 2.5 \text{ TeV}\]
Top Yukawa coupling measurement

important quantity that controls
EW vacuum stability, Higgs mass hierarchy
limited (~10%) sensitivity @ HL-LHC

hadron

lepton

\[ g \rightarrow H \rightarrow t \bar{t} \]

\[ g \rightarrow H \rightarrow t \bar{t} \]

\[ e^+ e^- \rightarrow t \bar{t} H \]

\[ e^+ e^- \rightarrow t \bar{t} H \]

\[ H \rightarrow \text{Higgs} @ FCC \]

\[ H \rightarrow \text{Higgs} @ FCC \]

\[ ttH/\bar{t}tZ \]

\[ H \rightarrow \text{production around 350 GeV} = \text{“hydrogen atom for strong interactions”, i.e. bound state free of nonperturbative quark confining interactions} \]
A number of studies have presented results combining measurements from different facilities. A unique superb measurement of ZH xs production is expected.

<table>
<thead>
<tr>
<th>$g_{HXY}$</th>
<th>Measurement Precision</th>
<th>FCC-ee</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>0.16%</td>
<td>0.16%</td>
<td>&lt;1% ?</td>
</tr>
<tr>
<td>WW</td>
<td>0.19%</td>
<td>0.19%</td>
<td>1% ?</td>
</tr>
<tr>
<td>$\gamma \gamma$</td>
<td>1.7%</td>
<td>1.7%</td>
<td>1% ?</td>
</tr>
<tr>
<td>$\tau \tau$</td>
<td>0.54%</td>
<td>0.54%</td>
<td>2% ?</td>
</tr>
<tr>
<td>$\mu \mu$</td>
<td>6.4%</td>
<td>6.4%</td>
<td>5% ?</td>
</tr>
<tr>
<td>uu,dd</td>
<td>H→Vγ, in progr.</td>
<td>H→Vγ, in progr.</td>
<td>5% ?</td>
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<tr>
<td>ee</td>
<td>$e^+e^→H$, in progr.</td>
<td>$e^+e^→H$, in progr.</td>
<td>&lt; $10^{-6}$ ?</td>
</tr>
</tbody>
</table>

adapted from M. Mangano, HXSWG ’15

Melbourne, July 4, 2016
Higgs self-couplings

The Higgs self-couplings plays important roles

(1) controls the stability of the EW vacuum
(2) dictates the dynamics of EW phase transition and potentially conditions the generation of a matter-antimatter asymmetry via EW baryogenesis

**hadron**

**lepton**

not an option for circular machines

relevant $350 \text{GeV} < E < 1 \text{TeV}$

relevant $E > 1 \text{TeV}$
HH production as a probe of HE couplings

\[ g \quad g \rightarrow h \quad h, \quad \sim c_t^2 \times \text{const.} \]

\[ g \quad t \rightarrow h, \quad \sim c_t c_3 \times \frac{m_h^2}{\hat{s}} \log^2 \left( \frac{m_t^2}{\hat{s}} \right) \]

\[ g \quad t \rightarrow h, \quad \sim c_{2t} \times \log^2 \left( \frac{m_t^2}{\hat{s}} \right) \]

\[ g \quad g \rightarrow h, \quad \sim c_g c_3 \frac{\alpha_s}{4\pi} \times \text{const.} \]

\[ g \quad g \rightarrow h, \quad \sim c_{2g} \frac{\alpha_s}{4\pi} \frac{\hat{s}}{v^2} \]

Azatov, Contino, Panico, Son '15
**Remarks:**

- unique access to $c_3$ but sensitivity is limited (within the validity of EFT?).
- statistically limited, with more luminosity
  - access to distribution
  - discriminating power $c_3$ vs. $c_{2t}$ vs $c_g$

Azatov, Contino, Panico, Son '15
see also Goertz, Papaefstathiou, Yang, Zurita '14
Extended Higgs sectors are a prediction of many BSM scenarios. They may play a role in the following open questions:

- (EW) Baryogenesis
- Identity of Dark Matter
- Smallness of the neutrino masses
- Naturalness of the EW scale

Modified scalar potential can lead to a 1st order EW phase transition

Type-II see-saw through extra scalars

Extended scalar sectors follow in natural theories:
  i) SUSY
  ii) Neutral Naturalness

A 100 TeV pp collider offers the unique opportunity to discover EW-charged or SM-singlet scalars with a few TeV mass

Contino FCC@Rome '16

Just one example for illustration: charged Higgs 95%CL exclusion

J. Hajer et al '15
Conclusions: breaking the HEP frontiers

new machines much wanted to
~~ open new horizons beyond LHC ~~
no lack of theoretical motivations
plenty of physics issues outside the SM frame
from
depth QFT questions
to
pressing phenomenological puzzles

synergy fuels progress

* no BSM major discovery without a thorough understanding of SM background
* challenge: control theoretical uncertainty to the level of experimental sensitivity
  * the cosmic/intensity/energy frontiers might be very much intertwined
* complementarity and synergy of electron and hadron machines
Conclusions: breaking the HEP frontiers

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H. Gray, FCC-ee Higgs workshop ’15

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Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies

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Physics Opportunities of a 100 TeV Proton-Proton Collider

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To know more

First look at the physics case of TLEP

Physics at the e+e- Linear Collider