Higgs Physics at the Future Circular Colliders (FCC)

Markus Klute (MIT)
EPS, Vienna
July 25th, 2015
International FCC collaboration to study

- pp-collider (FCC-hh)
- $e^+e^-$ collider (FCC-ee)
- p-e (FCC-he)

80-100 km infrastructure in Geneva area

Goal: CDR and cost review by 2018

Similar studies in China (50-70 km infrastructure)

- pp-collider (SppS)
- $e^+e^-$ collider (CepC)
# Future Circular Collider Program

<table>
<thead>
<tr>
<th></th>
<th>FCC-ee</th>
<th>FCC-ee</th>
<th>FCC-ee</th>
<th>FCC-ee</th>
<th>FCC-hh</th>
<th>FCC-ep</th>
</tr>
</thead>
<tbody>
<tr>
<td>√s [GeV]</td>
<td>90</td>
<td>160</td>
<td>240</td>
<td>350</td>
<td>100.000</td>
<td>3.464</td>
</tr>
<tr>
<td>Inst. luminosity [10^{34} cm^{-2}s^{-1}/IP]</td>
<td>215</td>
<td>38</td>
<td>8.8</td>
<td>2.5</td>
<td>5-30</td>
<td>6.2</td>
</tr>
<tr>
<td>L_{int} [ab^{-1}/year/IP]</td>
<td>21.5</td>
<td>3.8</td>
<td>0.9</td>
<td>0.25</td>
<td>0.3-1.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>1450</td>
<td>152</td>
<td>30</td>
<td>6.6</td>
<td>500-3000</td>
<td>480 / 500</td>
</tr>
</tbody>
</table>

**FCC-ee EW:** M. Dam  
**FCC-ee Top:** P. Janot  
**FCC-ee Flavor:** St. Monteil

![Graph showing luminoity vs. √s](image)
Higgs Production: FCC-ee
Precision Higgs Couplings

- Recoil method unique to lepton collider
- Tag Higgs event independent of decay mode
- Provide precision measurement of $\sigma(\text{ee} \rightarrow \text{ZH}) \propto g_{HZ}^2$
Measure $\sigma(\text{ee} \to ZH) \times \text{BR} (H \to X)$ by identifying $X$

Example: $\sigma(\text{ee} \to ZH) \times \text{BR} (H \to ZZ) \propto g_{HZ}^4/\Gamma_H$

Total width from combination of measurements or fit

Hadronic and invisible $Z$ decays increase precision

Branching fraction to invisible tested directly to 0.19% @ 95% CL

<table>
<thead>
<tr>
<th>Coupling</th>
<th>FCC-ee -240</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{HZZ}$</td>
<td>0.16%</td>
<td>0.15%</td>
</tr>
<tr>
<td>$g_{HWW}$</td>
<td>0.85%</td>
<td>0.19%</td>
</tr>
<tr>
<td>$g_{Hbb}$</td>
<td>0.88%</td>
<td>0.42%</td>
</tr>
<tr>
<td>$g_{Hcc}$</td>
<td>1.0%</td>
<td>0.71%</td>
</tr>
<tr>
<td>$g_{Hgg}$</td>
<td>1.1%</td>
<td>0.80%</td>
</tr>
<tr>
<td>$g_{H\tau\tau}$</td>
<td>0.94%</td>
<td>0.54%</td>
</tr>
<tr>
<td>$g_{H\mu\mu}$</td>
<td>6.4%</td>
<td>6.2%</td>
</tr>
<tr>
<td>$g_{H\gamma\gamma}$</td>
<td>1.7%</td>
<td>1.5%</td>
</tr>
<tr>
<td>BR_{exo}</td>
<td>0.48%</td>
<td>0.45%</td>
</tr>
</tbody>
</table>

stat. uncertainties
Higgs self-coupling through loop corrections

- Very large datasets at high energy allow extreme precision $g_{ZH}$ measurements
- Indirect and model-dependent probe of Higgs self-coupling
- Note, the time axis is missing from the plot

Matthew McCullough
arxiv:1312.3322
First generation couplings

- **s-channel Higgs production**
  - Unique opportunity for measurement close to SM sensitivity
  - Highly challenging; $\sigma(ee\rightarrow H) = 1.6\text{fb}$; various Higgs decay channels studied

- **Work in progress**
  - Loop-induced production channels have cross section than pure s-channel. But, how large are BSM effects?
  - Can monochromators yields energy spread of Higgs width or smaller? At what luminosity cost?
  - Energy scan $O(10\text{MeV})$ around $m_H$ will be needed to locate exact $\sqrt{s}$
  - Polarization increases cross section (e.g. by $x2$ at $P=70\%$). At what luminosity cost?

Preliminary Results

$L = 10 \text{ ab}^{-1}$

$\kappa_e < 2.2$ at $3\sigma$
CP violation can be studied by searching for CP-odd contributions; CP-even already established


Higgs to Tau decays of interest

\[ \mathcal{L}_{hff} \propto h\bar{f}(\cos \Delta + i\gamma_5 \sin \Delta)f \]

<table>
<thead>
<tr>
<th>Colliders</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>FCCee (1 ab(^{-1}))</th>
<th>FCCee (5 ab(^{-1}))</th>
<th>FCCee (10 ab(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy (1(\sigma))</td>
<td>25°</td>
<td>8.0°</td>
<td>5.5°</td>
<td>2.5°</td>
<td>1.7°</td>
</tr>
</tbody>
</table>

2,000,000 ZH events allow for detailed studies of rare and exotic decays
- requires hadronic and invisible Z decays
- set requirements for FCC-ee detector
Coupling measurements have sensitivity to BSM decays
Dedicated studies using specific final states improve sensitivity
Example: Higgs to invisible, flavor violating Higgs, and many more
Modes with limited LHC sensitivity are of particular importance to FCC-ee program
- currently under study
FCC-ee might allow precision measurement of exotic Higgs decays
### Higgs production: FCC-pp

<table>
<thead>
<tr>
<th>Process</th>
<th>8 TeV</th>
<th>14 TeV</th>
<th>100 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>gF</td>
<td>19.3 pb</td>
<td>50.35 pb</td>
<td>740.3 pb</td>
</tr>
<tr>
<td>VBF</td>
<td>1.58 pb</td>
<td>4.40 pb</td>
<td>82.0 pb</td>
</tr>
<tr>
<td>WH</td>
<td>0.70 pb</td>
<td>1.63 pb</td>
<td>15.9 pb</td>
</tr>
<tr>
<td>ZH</td>
<td>0.42 pb</td>
<td>0.90 pb</td>
<td>11.3 pb</td>
</tr>
<tr>
<td>ttH</td>
<td>0.13 pb</td>
<td>0.62 pb</td>
<td>37.9 pb</td>
</tr>
<tr>
<td>bbH</td>
<td>0.20 pb</td>
<td>0.58 pb</td>
<td>8.64 pb</td>
</tr>
<tr>
<td>gF to HH</td>
<td>8.15 fb</td>
<td>33.8 fb</td>
<td>1.42 fb</td>
</tr>
</tbody>
</table>

![Graph showing cross-sections for different processes at different energy levels](graph.png)

- $M_H = 125$ GeV
- MSTW2008

$\sigma$ [pb] vs. $\sqrt{s}$ [TeV]
### Higgs production: FCC-pp

<table>
<thead>
<tr>
<th>Process</th>
<th>8 TeV</th>
<th>14 TeV</th>
<th>100 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>gF</td>
<td>0.38</td>
<td>1</td>
<td>14.7</td>
</tr>
<tr>
<td>VBF</td>
<td>0.38</td>
<td>1</td>
<td>18.6</td>
</tr>
<tr>
<td>WH</td>
<td>0.43</td>
<td>1</td>
<td>9.7</td>
</tr>
<tr>
<td>ZH</td>
<td>0.47</td>
<td>1</td>
<td>12.5</td>
</tr>
<tr>
<td>ttH</td>
<td>0.21</td>
<td>1</td>
<td>61</td>
</tr>
<tr>
<td>bbH</td>
<td>0.34</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>gF to HH</td>
<td>0.24</td>
<td>1</td>
<td>42</td>
</tr>
</tbody>
</table>

- **Proton-proton Higgs datasets**
  - LHC Run I: x300-600
  - HL LHC: x10-400
  - FCC pp
Higgs physics program: FCC-pp

- Rare SM and non-SM decays
  - $\delta k_{\mu} \approx 2\%$ (extrapolated from LHC)
- Higgs self coupling
- BSM (heavy) Higgs boson production
- Cascade decays including Higgs bosons
- Differential cross section measurements
- … and in general a continuation of the LHC/HL-LHC program

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>VLHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (TeV)</td>
<td>14</td>
<td>33</td>
<td>100</td>
</tr>
<tr>
<td>$\int L dt$ (fb$^{-1}$)</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>$\sigma \cdot BR(pp \to HH \to bb\gamma\gamma)$ (fb)</td>
<td>0.089</td>
<td>0.545</td>
<td>3.73</td>
</tr>
<tr>
<td>$S/\sqrt{B}$</td>
<td>2.3</td>
<td>6.2</td>
<td>15.0</td>
</tr>
<tr>
<td>$\lambda$ (stat)</td>
<td>50%</td>
<td>20%</td>
<td>8%</td>
</tr>
</tbody>
</table>

arXiv:1310.8361
### Key question is the evolution systematic uncertainty

### FCC-pp analyses need to explore the size of the dataset to limit systematic uncertainties and require theoretical improvements
... but also new measurements are possible

\[
\begin{align*}
\text{ttH} / \text{ttZ} \\
\text{vs}
\end{align*}
\]

- Theoretical uncertainties cancel mostly
  - PDF (CTEQ 6.6) $\pm 0.5\%$
  - Missing higher orders $\pm 1.2\%$

- Complementarity with FCC-ee program
  - ttZ coupling can be measured with precision by FCC-ee
  - Higgs branching fraction

- Opens the possibility to measure top-Yukawa coupling with percent level precision
- More studies are needed to verify that $<1\%$ level target can be reached
### FCC Higgs physics program

<table>
<thead>
<tr>
<th></th>
<th>gH_{XY}</th>
<th>ZZ</th>
<th>WW</th>
<th>γγ</th>
<th>Zγ</th>
<th>tt</th>
<th>bb</th>
<th>ττ</th>
<th>cc</th>
<th>ss</th>
<th>μμ</th>
<th>uu,dd</th>
<th>ee</th>
<th>Γ_H</th>
<th>HH</th>
<th>BR_{exo}</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC-ee</td>
<td>0.15</td>
<td>0.19</td>
<td>1.5</td>
<td>0.42</td>
<td>0.54</td>
<td>0.71</td>
<td>H→V_{γ}</td>
<td>6.2</td>
<td>H→V_{γ} ee→H</td>
<td>0.9</td>
<td></td>
<td>0.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Summary of FCC-ee studies and “guesses” for FCC-hh performance. Uncertainty in %.
- Almost perfect complementarity between FCC-ee and FCC-hh program
Conclusion

- Exploration of Higgs Physics at the LHC on its way
  - HL-LHC will set a high bar for Higgs physics
- Exciting FCC Higgs program opens new windows
  - Complementarity of FCC-ee, ep, and pp
- Need significant theoretical improvements to exploit full potential
- Substantial program of work ahead in FCC study
  - Novel ideas appeared in recent workshops
  - Many opportunities to contribute
- **Goal:** CDR and cost review by 2018
References / Input from

- s-channel Higgs production: D.d'Enterria, R.Aleksan, G.Wojcik
- FCC-ep: M.Klein
- CMS: Snowmass report, ECFA report
- CP measurement: [http://arxiv.org/abs/1308.1094](http://arxiv.org/abs/1308.1094), Felix Xu’s meeting in the meeting
- Luminosity needs for FCC-hh and Higgs @ 100 TeV: M.Mangano
- Exclusive Higgs decays: Y. Soreq
- …
Higgs Production: FCC-ep

- FCC-ep can deliver PDFs for FCC-pp (Higgs) program
- Higgs studies in relatively clean environment
- Higgs precision $\kappa_b$ measurement, < 1%
- Investigation potential of $\kappa_c$ measurement using charm tagging
- Potential for Higgs self coupling studies
Status of Higgs studies at the LHC

» Fantastic progress in last 3 years

- Observation in three boson channels
- Evidence for fermion couplings
- Precision mass measurements: $125.09 \pm 0.24$ GeV (ATLAS+CMS)
- Spin/parity determined
- Higgs total width from off-shell production
- First results on differential cross sections

» New particle looks more and more like the SM Higgs boson

- No evidence for non-SM decays
- No evidence for additional Higgs bosons
How large are potential deviations from BSM physics?

How well do we need to measure Higgs couplings?

- To be sensitive to a deviation $\delta$, the measurement needs a precision of at least $\delta/3$, better $\delta/5$
- Implications of new physics scale on couplings from heavy states or through mixing

$$g = g_{SM} \left[ 1 + \Delta \right]: \quad \Delta = \mathcal{O}(v^2/\Lambda^2)$$

Percent-level precision needed to test TeV scale

There is no strict limit to the precision needed!
Higgs prospects for the HL-LHC

Coupling precision 2-10 %, factor 2-3 improvement from HL-LHC

Key question is the evolution systematic uncertainty

CMS Projection for precision of Higgs coupling measurement

<table>
<thead>
<tr>
<th>L (fb⁻¹)</th>
<th>κγ</th>
<th>κW</th>
<th>κZ</th>
<th>κg</th>
<th>κb</th>
<th>κt</th>
<th>κτ</th>
<th>κZγ</th>
<th>κμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</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>
</tr>
<tr>
<td>3000</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>
</tr>
</tbody>
</table>

ATLAS Simulation Preliminary

ś = 14 TeV: \( \int L dt = 300 \, fb^{-1} \); \( \int L dt = 3000 \, fb^{-1} \)
Di-Higgs production: exciting prospects of the HL-LHC

- Gluon fusion cross section is only 40.2 fb [NNLO] at 14 TeV
- Vector boson fusion cross section is 2 fb

Most interesting final states

- $bb\gamma\gamma$ [320 expected events in 3ab-1]
- $bb\tau\tau$ [9000 expected]
- $bbbb$ [40k expected (2k in VBF)]
- $bbWW$ [30000 exp. events]

Goal is to reach minimum sensitivity of $3\sigma$ for SM production and with that to BSM scenarios

<table>
<thead>
<tr>
<th>Process / Selection Stage</th>
<th>$HH$</th>
<th>$ZH$</th>
<th>$ttH$</th>
<th>$bbH$</th>
<th>$\gamma\gamma+$jets</th>
<th>$\gamma+$jets</th>
<th>jets</th>
<th>$tt\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object Selection &amp; Fit Mass Window</td>
<td>22.8</td>
<td>29.6</td>
<td>178</td>
<td>6.3</td>
<td>2891</td>
<td>1616</td>
<td>292</td>
<td>113</td>
</tr>
<tr>
<td>Kinematic Selection</td>
<td>14.6</td>
<td>14.6</td>
<td>3.3</td>
<td>2.0</td>
<td>128</td>
<td>96.9</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Mass Windows</td>
<td>9.9</td>
<td>3.3</td>
<td>1.5</td>
<td>0.8</td>
<td>8.5</td>
<td>6.3</td>
<td>1.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>

CMS - central photon yield
Exclusive Higgs boson decays

- First and second generation couplings accessible
  - Study of $g\gamma$ channel most promising; expect ~50 evts.
  - Sensitivity to $u/d$ quark Yukawa coupling
  - Sensitivity due to interference

Also interesting to FCC-hh program

Alternative $H \rightarrow MV$ decays should be studied ($V=\gamma, W, \text{and } Z$)

$$\begin{align*}
\text{BR}_{h \rightarrow \rho \gamma} &= \frac{\kappa_\gamma [(1.9 \pm 0.15)\kappa_\gamma - 0.24\kappa_u - 0.12\kappa_d]}{0.57\kappa_b^2} \times 10^{-5} \\
\text{BR}_{h \rightarrow b \bar{b}}
\end{align*}$$
Higgs Physics at the FCC-ee

- Precision Higgs coupling studies and total width
- Higgs self coupling through loop corrections
- 1st and 2nd fermion generation couplings
- Rare and exotic decays (e.g. DM decays)
- Extra Higgs bosons
- Tensor structure
- ...