Future Circular Collider - a short introduction
Future Circular Collider Study

International FCC collaboration with CERN as host lab to study:

- ~100 km tunnel infrastructure in Geneva area and linked to CERN
- $e^+e^-$ collider (FCC-ee) as potential first step
- pp-collider (FCC-hh) as long-term goal, defining the infrastructure requirements
  - ~16T $\Rightarrow$ 100 TeV pp in 100 km
- HE-LHC with FCC-hh technology
- Ion and lepton-hadron options with hadron collider
FCC Results

4 CDR volumes published in EPJ

FCC Physics Opportunities

Copies can be requested at http://get-fcc-cdr.web.cern.ch
FCC Program

Program in two phases

- **Phase 1:** FCC-ee (Z, W, H, tt) as Higgs, EW and top factory at highest luminosities.
- **Phase 2:** FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.
FCC project plan is fully integrated with HL-LHC exploitation and provides seamless continuation of high energy physics at the energy frontier
FCC-ee Operations

- A fantastic **Higgs factory** and much more
- **Higgs factory**
  - $10^6 \, e^+e^- \rightarrow HZ$
- **EW & Top factory**
  - $3 \times 10^{12} \, e^+e^- \rightarrow Z$
  - $10^8 \, e^+e^- \rightarrow W^+W^- ; \, 10^6 \, e^+e^- \rightarrow tt$
  - Transverse polarization
  - Sensitive to NP up to 100 TeV
- **Flavor factory**
  - $5 \times 10^{12} \, e^+e^- \rightarrow bb, cc ; \, 10^{11} \, e^+e^- \rightarrow \tau^+\tau^-$
- **Precision tool**
  - QED: $(m_Z)$, QCD $(m_Z)$, $10^5 \, H \rightarrow gg$
- **Potential discovery of NP**
  - ALPs, RH $\nu$'s, ...

Schedule basis for CDR physics result. Can be modified or optimized!
## FCC-ee Higgs Couplings

### Unique measurements at highest precision

<table>
<thead>
<tr>
<th>Collider</th>
<th>HL-LHC</th>
<th>ILC$_{250}$</th>
<th>CLIC$_{380}$</th>
<th>FCC-ee</th>
<th>FCC-eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity ($ab^{-1}$)</td>
<td>3</td>
<td>2</td>
<td>0.5</td>
<td>5 $@$ 240 GeV, +1.5 $@$ 365 GeV</td>
<td>+ HL-LHC 2</td>
</tr>
<tr>
<td>Years</td>
<td>25</td>
<td>15</td>
<td>8</td>
<td>3</td>
<td>+4</td>
</tr>
<tr>
<td>$\delta \Gamma_H / \Gamma_H$ (%)</td>
<td>SM</td>
<td>3.6</td>
<td>4.7</td>
<td>2.7</td>
<td>1.3</td>
</tr>
<tr>
<td>$\delta g_{HZZ} / g_{HZZ}$ (%)</td>
<td>1.5</td>
<td>0.30</td>
<td>0.60</td>
<td>0.2</td>
<td>0.17</td>
</tr>
<tr>
<td>$\delta g_{HWW} / g_{HWW}$ (%)</td>
<td>1.7</td>
<td>1.7</td>
<td>1.0</td>
<td>1.3</td>
<td>0.43</td>
</tr>
<tr>
<td>$\delta g_{Hbb} / g_{Hbb}$ (%)</td>
<td>3.7</td>
<td>1.7</td>
<td>2.1</td>
<td>1.3</td>
<td>0.61</td>
</tr>
<tr>
<td>$\delta g_{Hcc} / g_{Hcc}$ (%)</td>
<td>SM</td>
<td>2.3</td>
<td>4.4</td>
<td>1.7</td>
<td>1.21</td>
</tr>
<tr>
<td>$\delta g_{Hgg} / g_{Hgg}$ (%)</td>
<td>2.5</td>
<td>2.2</td>
<td>2.6</td>
<td>1.6</td>
<td>1.01</td>
</tr>
<tr>
<td>$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)</td>
<td>1.9</td>
<td>1.9</td>
<td>3.1</td>
<td>1.4</td>
<td>0.74</td>
</tr>
<tr>
<td>$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)</td>
<td>4.3</td>
<td>14.1</td>
<td>n.a.</td>
<td>10.1</td>
<td>9.0</td>
</tr>
<tr>
<td>$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)</td>
<td>1.8</td>
<td>6.4</td>
<td>n.a.</td>
<td>4.8</td>
<td>3.9</td>
</tr>
<tr>
<td>$\delta g_{Htt} / g_{Htt}$ (%)</td>
<td>3.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>BR$_{EXO}$ (%)</td>
<td>SM</td>
<td>&lt;1.8</td>
<td>&lt;3.0</td>
<td>&lt;1.2</td>
<td>&lt;1.0</td>
</tr>
</tbody>
</table>

### Uncertainties not limited by experimental or theoretical uncertainties. Statistics sets the floor.

### Indirect sensitivity to Higgs self-coupling
### First set of main observables

- **Statistical precision follows straight forward**
- **For Z and W boson mass, center-of-mass energy uncertainty will dominate**
- **For cross-section measurements the luminosity measurement will be limiting**
- **Possible experimental uncertainties are indicative**

#### Table 3.1 Measurement of selected electroweak quantities at the FCC-ee, compared with the present precisions

<table>
<thead>
<tr>
<th>Observable</th>
<th>Present value ± error</th>
<th>FCC-ee Stat.</th>
<th>FCC-ee Syst.</th>
<th>Comment and dominant exp. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z$ (keV)</td>
<td>91,186,700 ± 2200</td>
<td>5</td>
<td>100</td>
<td>From Z line shape scan Beam energy calibration</td>
</tr>
<tr>
<td>$\Gamma_Z$ (keV)</td>
<td>2,495,200 ± 2300</td>
<td>8</td>
<td>100</td>
<td>From Z line shape scan Beam energy calibration</td>
</tr>
<tr>
<td>$R^Z$ ((\times 10^3))</td>
<td>20,767 ± 25</td>
<td>0.06</td>
<td>0.2–1.0</td>
<td>Ratio of hadrons to leptons acceptance for leptons</td>
</tr>
<tr>
<td>$\alpha_s$ ((m_Z) \times 10^4)</td>
<td>1196 ± 30</td>
<td>0.1</td>
<td>0.4–1.6</td>
<td>From $R^Z$ above [43]</td>
</tr>
<tr>
<td>$R_h$ ((\times 10^6))</td>
<td>216,290 ± 660</td>
<td>0.3</td>
<td>&lt; 60</td>
<td>Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [44]</td>
</tr>
<tr>
<td>$\sigma_{had}$ ((\times 10^3)) ((nb))</td>
<td>41,541 ± 37</td>
<td>0.1</td>
<td>4</td>
<td>Peak hadronic cross-section luminosity measurement</td>
</tr>
<tr>
<td>$N_p$ ((\times 10^3))</td>
<td>2991 ± 7</td>
<td>0.005</td>
<td>1</td>
<td>Z peak cross sections Luminosity measurement</td>
</tr>
<tr>
<td>$\sin^2\theta_W^{\text{eff}}$ ((\times 10^6))</td>
<td>231,480 ± 160</td>
<td>3</td>
<td>2–5</td>
<td>From $A_W^{\mu\mu}$ at Z peak Beam energy calibration</td>
</tr>
<tr>
<td>$1/\alpha_{\text{QED}}$ ((m_Z) \times 10^3)</td>
<td>128,952 ± 14</td>
<td>4</td>
<td>Small</td>
<td>From $A_W^{\mu\mu}$ off peak [34]</td>
</tr>
<tr>
<td>$A_{FB}^{b,0}$ ((\times 10^4))</td>
<td>992 ± 16</td>
<td>0.02</td>
<td>1–3</td>
<td>b-quark asymmetry at Z pole from jet charge</td>
</tr>
<tr>
<td>$A_{FB}^{\text{pol},r}$ ((\times 10^4))</td>
<td>1498 ± 49</td>
<td>0.15</td>
<td>&lt; 2</td>
<td>$\tau$ Polarisation and charge asymmetry $\tau$ decay physics</td>
</tr>
<tr>
<td>$m_W$ (MeV)</td>
<td>80,350 ± 15</td>
<td>0.5</td>
<td>0.3</td>
<td>From WW threshold scan Beam energy calibration</td>
</tr>
<tr>
<td>$\Gamma_W$ (MeV)</td>
<td>2085 ± 42</td>
<td>1.2</td>
<td>0.3</td>
<td>From WW threshold scan Beam energy calibration</td>
</tr>
<tr>
<td>$\alpha_s$ ((m_W) \times 10^4)</td>
<td>1170 ± 420</td>
<td>3</td>
<td>Small</td>
<td>From $R^W$ [45]</td>
</tr>
<tr>
<td>$N_v$ ((\times 10^3))</td>
<td>2920 ± 50</td>
<td>0.8</td>
<td>Small</td>
<td>Ratio of invis. to leptonic in radiative Z returns</td>
</tr>
<tr>
<td>$m_{\text{top}}$ (MeV)</td>
<td>172,740 ± 500</td>
<td>17</td>
<td>Small</td>
<td>From $t\bar{t}$ threshold scan QCD errors dominate</td>
</tr>
<tr>
<td>$\Gamma_{\text{top}}$ (MeV)</td>
<td>1410 ± 190</td>
<td>45</td>
<td>Small</td>
<td>From $t\bar{t}$ threshold scan QCD errors dominate</td>
</tr>
<tr>
<td>$\lambda_{\text{top}}/\lambda_{\text{SM}}$</td>
<td>1.2 ± 0.3</td>
<td>0.1</td>
<td>Small</td>
<td>From $t\bar{t}$ threshold scan QCD errors dominate</td>
</tr>
<tr>
<td>$t\bar{t}Z$ couplings</td>
<td>$\pm$ 30%</td>
<td>0.5–1.5%</td>
<td>Small</td>
<td>From $E_{CM} = 365$ GeV run</td>
</tr>
</tbody>
</table>
First generation Higgs couplings

- Not part of baseline run plan but a few years at $\sqrt{s} = m_H$ with high luminosity is an interesting add-on

- Expected signal significance of $0.4\sigma / \sqrt{\text{year}}$ in option 1 and 2 (see below)
  - Set a electron Yukawa coupling upper limit: $\kappa_e < 2.5$ @95% CL
  - Reaches SM sensitivity after 5 years

![Graph](image-url)
Possible FCC-ee discoveries

- Exploring 10-100 TeV energy scale with precision measurements
  - “Model independent” Higgs couplings
  - Higgs self couplings
  - $m_Z$, $m_W$, $m_{\text{top}}$, $\sin^2\Theta_w^{\text{eff}}$, $R^b$, $\alpha_{\text{QED}}(m_Z,m_W,m_\tau)$, top quark couplings
- Discovery of dark matter as invisible decays of H or others
- Discovery of very weakly coupled particles in 5-100 GeV range such as RH neutrinos, dark photons, ALPS, etc
- Discoveries in flavor physics and many more opportunities
- EW precision program essential to maximize Higgs factories potential
FCC-ee Detectors

Two detector concepts studied for integration, performance and cost estimates:

- Linear Collider Detector group at CERN has undertaken the adaption of CLIC-SID detector for FCC-ee
- IDEA, detector specifically designed for FCC-ee (and CEPC)

Next step is in optimizing detectors for physics
European Strategy

2013: To stay at the forefront of particle physics … CERN should undertake design studies … with emphasis on proton-proton and electron-positron high-energy frontier machines


2020: Recommendation discussed at March 15th CERN Council meeting but the meeting to endorse the strategy in May has been cancelled due to COVID-19
**FCC Main Goals (2020-2026)**

**Overall goal**
- Perform all necessary steps and studies to enable a definitive project decision by 2025/26, at the anticipated date for the next ESU, and a subsequent start of civil engineering construction by 2028/29.

**This requires successful completion of the following four main activities**
- Develop and establish a governance model for project construction and operation
- Develop and establish a financing strategy
- Prepare and successfully complete all required project preparatory and administrative processes with the host states (debat public, EIA, etc.)
- Perform site investigations to enable CE planning and to prepare CE tendering.

**In parallel development preparation of TDRs and physics/experiment studies**
- Machine designs and main technology R&D lines
- Establish user communities, work towards proto-experiment collaboration by 2025/26.
International FCC study focused on the conceptual design of high-performance energy frontier circular colliders for the post-LHC era.

The first phase of FCC conceptual design studies is completed.

Baseline machine designs and associated infrastructures, with performance matching the physics requirements, were established and are documented in 4 CDRs.

Conditional on European Strategy recommendations, the next steps will develop a concrete implementation plan in collaboration with host states, accompanied by machine optimization, physics studies and technology R&D.
FCC-ee is a Z, W, H, top (and NP) factory with **exciting opportunities**

FCC-ee Higgs factory offers a unique dataset from 240 to 365 GeV
- Delivers model-independent precision measurements of Higgs properties
- Couplings including self-coupling, mass, CP, …
- The floor is statistical

EW and Higgs observables probe the scales to up to 50 TeV
- Gain of 1-2 orders of magnitude in precision
- EW precision measurements enable high accuracy Higgs program

Synergy and complementarity to hadron collider physics programs (HL-LHC, FCC-hh)
4 CDR volumes

First look at the physics case of TLEP

- JHEP 1401 (2014) 164; > 500 citations

FCC The Lepton Collider


FCC Physics Opportunities


FCC-ee: Your Questions Answered

- arXiv:1906.02693

Jan’20 FCC physics workshop

- https://indico.cern.ch/event/838435/