Future Circular Collider Study
Overview and Design Status

M. Koratzinos
On behalf of the FCC design study team

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http://cern.ch/fcc
International FCC collaboration (CERN as host lab) to study:

- ~100 km tunnel infrastructure in Geneva area, linked to CERN
- $e^+e^-$ collider (FCC-ee), as potential first step
- $pp$-collider (FCC-hh) → long-term goal, defining infrastructure requirements
- HE-LHC with FCC-hh technology

FCC CDRs are now available

$\sim 16 \, T \Rightarrow 100 \, \text{TeV} \, pp \, \text{in} \, 100 \, \text{km}$
FCC in the plenary sessions in this conference:
• FCC status (this talk)
• FCC-ee status, Mogens Dam
• FCC-hh and HE-LHC, Michelangelo Mangano

I would like to thank everybody in the FCC study and all the signatories of the CDR. I have taken material from talks given by: Michael Benedikt, Fabiola Gianotti, Frank Zimmermann, Patrick Janot, Katsunobu Oide, as well as material from the CDRs.
FCC study: CDR released on 15 January 2019

International collaboration publishes concept design for a post-LHC future circular collider at CERN

Today, the Future Circular Collider (FCC) collaboration submitted its Conceptual Design Report (CDR) for publication

15 JANUARY, 2019
FCC study: CDR released on 15 January 2019

Conceptual Design Report Volumes

European Strategy Update Documents

Future Circular Collider Study

Statement from the FCC International Advisory Committee

Press Kit

M. Koratzinos, IAS HKUST 2019
Future Circular Collider (FCC)

<table>
<thead>
<tr>
<th>√s</th>
<th>L /IP (cm⁻² s⁻¹)</th>
<th>Int. L /IP(ab⁻¹)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁺e</td>
<td>-90 GeV Z</td>
<td>230 x10³⁴</td>
<td>75 ab⁻¹</td>
</tr>
<tr>
<td></td>
<td>160 WW</td>
<td>28</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>240 H</td>
<td>8.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>-355 top</td>
<td>1.5</td>
<td>0.8</td>
</tr>
<tr>
<td>pp</td>
<td>100 TeV</td>
<td>5 x 10³⁴</td>
<td>2.5 ab⁻¹</td>
</tr>
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<td></td>
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<td>30</td>
<td>15</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>PbPb</td>
<td>√s_{NN} = 39TeV</td>
<td>3 x 10²⁹</td>
<td>100 nb⁻¹/run</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ep</td>
<td>3.5 TeV</td>
<td>1.5 x10³⁴</td>
<td>2 ab⁻¹</td>
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<td></td>
</tr>
<tr>
<td>e-Pb</td>
<td>√s_{NN} = 2.2 TeV</td>
<td>0.5 x10³⁴</td>
<td>1 fb⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
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</table>

Also studied: HE-LHC: √s=27 TeV using FCC-hh
16 T magnets in LHC tunnel; L~1.6x10³⁵ → 15 ab⁻¹ for 20 years operation

Sequential implementation, FCC-ee followed by FCC-hh, would enable:
- variety of collisions (ee, pp, PbPb, eh) → impressive breadth of programme, 6++ experiments
- exploiting synergies by combining complementary physics reach and information of different colliders → maximise indirect and direct discovery potential for new physics
- starting with technologically ready machine (FCC-ee); developing in parallel best technology (e.g. HTS magnets) for highest pp energy (100++ TeV)
- building stepwise at each stage on existing accelerator complex and technical infrastructure

Purely technical schedule, assuming green light to preparation work in 2020.
A 70 years programme

<table>
<thead>
<tr>
<th>8 years preparation</th>
<th>10 years tunnel and FCC-ee construction</th>
<th>15 years FCC-ee operation</th>
<th>11 years FCC-hh preparation and installation</th>
<th>25 years FCC-hh operation pp/PbPb/eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020-2028</td>
<td>2038-2053</td>
<td>2064-2090</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
$5 \times 10^{12} Z$ (10$^5$ x LEP), $10^8$ WW (10$^3$ x LEP), $10^6$ H (not yet in $e^+e^-$), $10^6$ tt (not yet in $e^+e^-$)

- Unprecedentedly precise measurements of Higgs couplings (model-independent) and EW parameters with x10-50 improvement on current precision → indirect sensitivity to new physics up to $\Lambda \sim 100$ TeV
  → pattern of deviations may indicate specific scenarios for new physics
- Searches for ultra-rare/forbidden decays (e.g. $Z \rightarrow \tau \mu$) and new particles with very small couplings

Note: need improved theoretical calculations to match experimental precision → strategic investment
FCC-hh Simulation (Delphes), $\sqrt{s} = 100$ TeV

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

5 $\sigma$ Discovery

- 2.5 ab$^{-1}$
- 30 ab$^{-1}$
- 100 ab$^{-1}$

Matter up to mass upper limits of 1-3 TeV receded sensitivity to rare decays use transition

**Technical challenges!!** Examples:
- Id superconducting magnets ($\geq 16$ T)
- Cfr. LHC: 15 kW power load in arcs from proton radiation $\rightarrow$ cryogenics, vacuum beam energy (8 GJ, 12 x HL-LHC)
- In the detectors ($\sim 1000$ events/xing)
- Energy consumption: 4 TWh/year ($\sim 3$ x HL-LHC)

F. Gianotti 15/1/2019
"Ultimate" precision on the Higgs coupling measurements by combining the results from HL-LHC and each FCC collider sequentially.

Number of Higgs bosons produced:
- FCC-ee: $10^6$
- FCC-eh: $2 \times 10^6$
- FCC-hh: $10^{10}$

One-sigma precision reach at the FCC on the different Higgs coupling scaling factors within the $\kappa$-framework.

Note: input from FCC-ee (e.g. HZZ coupling) removes model-dependence of several couplings that are best measured at FCC-HH (e.g. ttH, $H \rightarrow \mu \mu$, $H \rightarrow ZZ\gamma$)
FCC-ee
FCC-ee basic design choices

- **Double ring** e+ e- collider ~100 km
- **Common footprint with FCC-hh**, except around IPs
- **Asymmetric IR layout and optics** to limit synchrotron radiation towards the detector
- **2 IPs, large** horizontal crossing angle 30 mrad, crab-waist optics
- **Synchrotron radiation power** 50 MW/beam at all beam energies
- **Top-up injection** scheme for high luminosity
- Requires **booster synchrotron in collider tunnel**
## FCC-ee collider parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-ee</th>
<th>LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy/beam [GeV]</td>
<td>45</td>
<td>105</td>
</tr>
<tr>
<td>bunches/beam</td>
<td>16640</td>
<td>48</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>1390</td>
<td>5.4</td>
</tr>
<tr>
<td>luminosity/IP x 10^{34} cm^{-2}s^{-1}</td>
<td>230</td>
<td>1.5</td>
</tr>
<tr>
<td>energy loss/turn [GeV]</td>
<td>0.036</td>
<td>9.2</td>
</tr>
<tr>
<td>total synchrotron power [MW]</td>
<td>100</td>
<td>22</td>
</tr>
<tr>
<td>RF voltage [GV]</td>
<td>0.1</td>
<td>4+6.9</td>
</tr>
<tr>
<td>rms bunch length (SR,+BS) [mm]</td>
<td>3.5, 12</td>
<td>12, 12</td>
</tr>
<tr>
<td>rms emittance e_{x,y} [nm, pm]</td>
<td>0.3, 1.0</td>
<td>22, 250</td>
</tr>
<tr>
<td>Horiz.,vertical beta* [mm]</td>
<td>150, 0.8</td>
<td>1000, 1.6</td>
</tr>
<tr>
<td>longit. damping time [turns]</td>
<td>1273</td>
<td>20</td>
</tr>
<tr>
<td>crossing angle [mrad]</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>beam lifetime (rad.B+BS) [min]</td>
<td>68</td>
<td>434</td>
</tr>
</tbody>
</table>
Lepton collider luminosities

<table>
<thead>
<tr>
<th>Lepton collider</th>
<th>c.m. energy [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>91</td>
</tr>
<tr>
<td>WW</td>
<td>160</td>
</tr>
<tr>
<td>ZH</td>
<td>240</td>
</tr>
<tr>
<td>ttbar</td>
<td>350</td>
</tr>
</tbody>
</table>

![Graph showing lepton collider luminosities](image-url)

- **FCC-ee (2IPs) - CDR**
- **CEPC (2IPs) - CDR**
- **ILC250, staged updated**
- **CLIC**
### FCC-ee operation model

<table>
<thead>
<tr>
<th>working point</th>
<th>luminosity/IP $[10^{34} \text{ cm}^{-2}\text{s}^{-1}]$</th>
<th>Integrated lumi/y (2 IPs)</th>
<th>physics goal</th>
<th>run period [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$ first 2 years</td>
<td>100</td>
<td>26 ab$^{-1}$/year</td>
<td>150 ab$^{-1}$</td>
<td>4</td>
</tr>
<tr>
<td>$Z$ thereafter</td>
<td>200</td>
<td>48 ab$^{-1}$/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W$</td>
<td>25</td>
<td>6 ab$^{-1}$/year</td>
<td>10 ab$^{-1}$</td>
<td>2</td>
</tr>
<tr>
<td>$H$</td>
<td>7.0</td>
<td>1.7 ab$^{-1}$/year</td>
<td>5 ab$^{-1}$</td>
<td>3</td>
</tr>
</tbody>
</table>

Machine modification for RF installation & rearrangement: **1 year**

<table>
<thead>
<tr>
<th></th>
<th>integrated lumi/y/year</th>
<th>physics goal</th>
<th>run period [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>top 1st year (350 GeV)</td>
<td>0.8</td>
<td>0.2 ab$^{-1}$/year</td>
<td>0.2 ab$^{-1}$</td>
</tr>
<tr>
<td>top thereafter (365 GeV)</td>
<td>1.4</td>
<td>0.34 ab$^{-1}$/year</td>
<td>1.5 ab$^{-1}$</td>
</tr>
</tbody>
</table>

**Total program duration: 15 years** - *including machine modifications*

**Phase 1 ($Z, W, H$): 9 years, phase 2 (top): 6 years**
FCC-ee RF staging scenario

three sets of RF cavities to cover all options for FCC-ee & booster:

- high intensity (Z, FCC-hh): 400 MHz mono-cell cavities (4/cryom.)
- higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)
- ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)
- installation sequence comparable to LEP (≈ 30 CM/shutdown)

<table>
<thead>
<tr>
<th>WP</th>
<th>V_{rf} [GV]</th>
<th>#bunches</th>
<th>I_{beam} [mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>0.1</td>
<td>16640</td>
<td>1390</td>
</tr>
<tr>
<td>W</td>
<td>0.44</td>
<td>2000</td>
<td>147</td>
</tr>
<tr>
<td>H</td>
<td>2.0</td>
<td>393</td>
<td>29</td>
</tr>
<tr>
<td>ttbar</td>
<td>10.9</td>
<td>48</td>
<td>5.4</td>
</tr>
</tbody>
</table>
Two different concepts have been demonstrated to work, one a proven concept and the other with a thin solenoid and simple calorimeter (and a factor 2 cheaper)

We are now open to detector collaborations!
FCC-ee key R&D
Progress with SRF cavity R&D program

5-cell 800 MHz cavity, JLAB prototype for both FCC-ee (t-tbar) & FCC-eh ERL (PERLE)

Seamless 400 MHz single-cell cavity formed by spinning at INFN-LNL

CERN half-cells formed using Electro-Hydro-Forming (EHF) at Bmax.

High strain rate technology using shockwaves in water from HV discharge. EHF investigated for half-cells and seamless Nb and Cu cavities.

JLAB, Oct 25, 2017  F. Marhauser et al

Legnaro, Feb 2018  V. Palmieri †  C. Pira

Tooling fabricated and successfully tested with an Aluminium cavity.
Prototypes of FCC-ee low-power magnets

Power-saving twin-dipole design: 16 MW (at 175 GeV), with Aluminium busbars

Power-saving twin F/D quad design: 25 MW (at 175 GeV), with Copper conductor

FCC-ee non-superconducting magnet design: minimize power consumption
The chambers feature **lumped SR absorbers with NEG-pumps** placed next to them.

**Construction of chamber prototypes in coming months and integration with twin magnets**
FCC-hh
# FCC-pp collider parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>HE-LHC</th>
<th>HL-LHC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision energy CMS [TeV]</td>
<td>100</td>
<td>27</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Dipole field [T]</td>
<td>16</td>
<td>16</td>
<td>8.33</td>
<td>8.33</td>
</tr>
<tr>
<td>Circumference [km]</td>
<td>97.75</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>0.5</td>
<td>1.27</td>
<td>1.1</td>
<td>0.58</td>
</tr>
<tr>
<td>Bunch intensity [$10^{11}$]</td>
<td>1</td>
<td>1</td>
<td>2.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Synch. rad. power / ring [kW]</td>
<td>2400</td>
<td>101</td>
<td>7.3</td>
<td>3.6</td>
</tr>
<tr>
<td>SR power / length [W/m/ap.]</td>
<td>28.4</td>
<td>4.1</td>
<td>0.33</td>
<td>0.17</td>
</tr>
<tr>
<td>Long. emit. damping time [h]</td>
<td>0.54</td>
<td>1.8</td>
<td>12.9</td>
<td>12.9</td>
</tr>
<tr>
<td>Beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.45</td>
<td>0.15 (min.)</td>
</tr>
<tr>
<td>Normalized emittance [$\mu$m]</td>
<td>2.2</td>
<td>2.5</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>Peak luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>5</td>
<td>30</td>
<td>16</td>
<td>5 (lev.)</td>
</tr>
<tr>
<td>Events/bunch crossing</td>
<td>170</td>
<td>1000</td>
<td>460</td>
<td>132</td>
</tr>
<tr>
<td>Stored energy/beam [GJ]</td>
<td>8.4</td>
<td>1.4</td>
<td>0.7</td>
<td>0.36</td>
</tr>
</tbody>
</table>
FCC-hh layout and optics

- circumference 97.8 km
- two high-luminosity experiments (A & G)
- two other experiments (L & B) combined with injection upstream of experiments
- two collimation insertions
  - betatron cleaning (J)
  - momentum cleaning (F)
- Extraction/dump insertion (D)
- RF insertion (H)
- integrated optics for full ring established, beam dynamics studies confirm design goals
FCC-hh injector options and transfer lines

**Baseline:**
LHC @ 3.3 TeV

**Alternative:**
scSPS @ 1.3 TeV

**Current baseline:**
- Injection energy 3.3 TeV LHC
  → Field-swing FCC-hh like LHC

**Alternative options:**
- Injection from SPS\textsubscript{upgrade} around 1.3 TeV
- SPS\textsubscript{upgrade} could be based on fast-cycling SC magnets, 6-7T, ~1T/s ramp, cf. SIS 300 design
- SPS\textsubscript{upgrade} would also be an ideal injector for HE LHC (as alternative to the 450 GeV SPS)
16 T dipole design activities and options

Short model magnets (1.5 m lengths) will be built from 2018 – 2022
Russian 16 T magnet program coordinated by BINP.
Successful test of FCC-hh beam screen

Synchrotron radiation 28W/m/beam (@16 T field) (cf. LHC <0.2W/m) ~ 5.6 MW total load in arcs
- absorption of synchrotron radiation at a higher temperature than 1.8 K for cryogenic efficiency
- provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.

FCC-hh beam-screen test set-up at ANKA/Germany:
beam tests with three prototype beam screens, confirming vacuum design simulations

KARA $e^-$ photon spectrum = FCC –hh spectrum

2.5 GeV ANKA/KIT storage ring
Present baseline position was established considering:

- lowest risk for construction
- fastest and cheapest construction
- feasible positions for large-span caverns (the most challenging structures)

next step: review of surface site locations and machine layout
FCC – tunnel integration in arcs

FCC-ee  
FCC-hh
5.5 m inner diameter
Civil Engineering schedule studies

- Total duration of construction: 7 years
- First sector ready in 4.5 years
FCC liaison with Host States

General secretariat of the region Auvergne-Rhône-Alpes created body “Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement”

Working group established with representatives of the federation, the Canton and the state of Geneva. Swiss representatives to international organisations and consultancy companies are also present.

- Administrative processes for the preparatory phase of the project have been developed.
- First review of tunnel placement performed.
- Requirements for urban, environmental and economic impact, land acquisition and construction permit related processes defined.
- Optimization of collider tunnel and surface infrastructure sites planned for 2019.
**FCC integrated project technical timeline**

1. **Project preparation & administrative processes**
2. **Funding strategy**
   - Funding and in-kind contribution agreements
3. **Geological investigations, infrastructure detailed design and tendering preparation**
4. **Tunnel, site and technical infrastructure construction**
5. **Superconducting wire and magnet R&D**
6. **FCC-ee accelerator R&D and technical design**
7. **Set up of international experiment collaborations, detector R&D and concept development**
8. **FCC-ee detector technical design**
9. **FCC-ee detector construction, installation, commissioning**
10. **SC wire and high-field magnet R&D, models, prototypes**
11. **High field dipole magnet series production**
12. **FCC-ee dismantling, CE & infrastructure adaptations FCC-hh**
13. **FCC-hh detector R&D, technical design**
14. **FCC-hh detector construction, installation, commissioning**
15. **FCC-hh accelerator R&D and technical design**
16. **FCC-hh accelerator construction, installation, commissioning**
17. **Funding and in-kind contribution agreements**
18. **Update Permissions**

**Timeline**
- 1-18: 15 years operation
- 33-70: ~25 years operation

**Logistics**
- Civil Engineering
- Accelerators
- Detectors
### FCC cost estimates

#### FCC-ee alone
- Civil Engineering: 5'400 MCHF (51%)
- Technical Infrastructure: 2'000 MCHF (19%)
- Collider and injector complex: 3'100 MCHF (30%)

- Z, W, H programmes: 10,500 MCHF
- tt programme: 1,100 MCHF

**Figure 6:** FCC-ee capital expenditures per project domain (Z, W, H programmes only)

#### FCC integral project
- FCC-ee programmes: 11,600 MCHF
- FCC-hh programme (additional cost): 17,000 MCHF

**Total:**
- Civil engineering + infrastructure: 7,400 MCHF
- FCC-hh cost dominated by machine and injector costs (13,600 MCHF) – high field magnets: 9,400 MCHF

**Figure 10:** FCC-hh capital cost per domain for the integral FCC project.

**Economic efficiency of integral project:** about 7,000 MCHF compared to individual projects
Cost comparison of CEPC, FCC-ee

Note that the relative portion for civil engineering and technical infrastructure is much smaller in CEPC than FCC-ee.

The cost for FCC-ee roughly agrees with scaling from LEP (1/3.5) including ∼150% inflation adjustment of CHF since 1985.

K.Oide
FCC-ee: electricity cost vs luminosity delivered

- electricity cost ~260 euro per Higgs boson.

- twin-aperture arc magnets, thin-film SRF, efficient RF power sources, top-up injection

- FCC-ee average yearly consumption: 1.9TWh
- LEP2: 0.9 to 1.1TWh
- LHC today: 1.2TWh
- HiLumi LHC: 1.4TWh

F. Zimmermann
Status of Global FCC Collaboration

- 133 Institutes
- 25 Companies
- 34 Countries
- EC H2020
Final meeting of EuroCirCol DS (H2020 financed)

Some key topics:

- FCC physics
- Studies on tunnel implementation
- R&D progress on SRF and SCM
- FCC-ee: Injector chain MDI/IR optimisation
- Machine optimisation
- SRF R&D program
Conclusions

• The FCC study focuses on high-performance energy frontier circular colliders for the post-LHC era.

• The first phase of the FCC conceptual design studies is complete. It has established baseline machine designs with performance that matches the demanding physics requirements, documented in four CDR volumes.

• Worldwide R&D programs are in place on Nb$_3$Sn superconductor technology, high-field magnets and highly-efficient SC RF.

• The international FCC collaboration is growing steadily, there are many R&D opportunities and all the community is invited to join.

• Next step, in parallel to the ESU process, is developing of a specific implementation scenario, accompanied by machine optimization, physics studies and technology R&D.
Extra slides
Is a $\sqrt{s} = 500$ GeV upgrade required/useful?

- According to the white book of ESU 2013:
  
  At energies of 500 GeV or higher, such a machine could explore the Higgs properties further, for example the coupling to the top quark, the self-coupling, and the total width.

- The same arguments are used by some documents submitted to ESU 2020!
- So, should we foresee an upgrade of FCC-ee at $\sqrt{s} = 500$ GeV?
  - For the total width and the coupling to the top quark: the answer is NO (slide 14)
  - For the Higgs self-coupling ($\kappa_\lambda$):

At $\sqrt{s} = 500$ GeV

Di-Higgs production

M. McCullough
arXiv:1312.3322
https://cds.cern.ch/record/1567295/
Higgs self-coupling at the FCC-ee

- Effect of Higgs self coupling ($\kappa_\lambda$) on $\sigma_{ZH}$ and $\sigma_{\nu\nu H}$ depends on $\sqrt{s}$

  ![Effect of Higgs self coupling](image)

- Two energy points lift off the degeneracy between $\delta\kappa_Z$ and $\delta\kappa_H$
  - Precision on $\kappa_\lambda$ with 2 IPs at the end of the FCC-ee (91+160+240+365 GeV)
    - Global EFT fit (model-independent) : $\pm 34\%$ ; in the SM : $\pm 12\%$ (3$\sigma$)
    - Precision on $\kappa_\lambda$ with 4 IPs : $\pm 21\%$ (EFT fit) ; $\pm 9\%$ (SM fit) (5$\sigma$)
  - $\sim 5\sigma$ discovery · 5$\sigma$ discovery 1d of 2 – much less costly than 500 GeV upgrade

- And, most importantly
  - Only FCC-hh, in combination with FCC-ee, can measure $\kappa_{\text{top}}$ and $\kappa_\lambda$ to $1\%$ and $5\%$, resp.

See M. Aleksa's talk
recall the construction of LEP

<6 years from zero to physics
CERN energy consumption

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FCC-ee estimate
~300MW × 200 days = 1.4 TWh
electricity cost

facility electricity cost 2014/15 in Euro / MWh

1400 GWh / yr → ~70 MEuro / yr

Courtesy: M. Seidel, EuCARD-2, V. Shiltsev, K. Oide, Q. Qin, G. Trubnikov, and others
Measuring the beam energy and energy spread

• Measuring the beam energy and energy spread is essential at the Z and W running.

• We aim for errors of $\sim 100$ keV for ECM. Use the resonant depolarization method (transverse polarization needed)
  – Note that statistical error for the Z mass determination is only 5 keV ($5.10^{12}$ Zs!)
  – Also note that the daily variation of the energy due to terrestrial tides would be $\sim 130$ MeV
  – LEP experience: $M_Z$ measured to 2 MeV

• A working group has been set up (chaired by A. Blondel) and a workshop was organised at CERN

• Please note that measuring the beam energy necessitates the use of dedicated hardware, so it needs to be designed early.
The resonant depolarization method

\[ \nu = \alpha \gamma = \frac{ae}{mc^2} = \frac{E[\text{MeV}]}{440.6486(1)[\text{MeV}]} \]

- The spin tune of an electron in a storage ring, \( \nu \), is proportional to its energy.
- This energy can be measured (instantaneously) to \(~100\text{keV per beam!} \)
- Different effects change the beam energy by orders of magnitude larger than that!
- We have the LEP experience to assist us, but still need to do a factor 20 better than that.
- Unique to FCC-ee: the resonant depolarization method can be used not only for the running around the Z, but also for the WW running

Unique to circular colliders
Achieving polarization

Accurate energy determination is needed for: $M_Z$, $\Gamma_Z$, $M_W$, $\sin^2 \theta_W$ (from the muon F-B asymmetry at the Z)

- To depolarize you must first have achieved polarization; ~10% polarization sufficient
- A real (imperfect) machine depolarizes fast – need careful corrections to restore polarization levels
- Would this be possible? Simulation code SISTROS says yes both for the Z and for the W. Correcting an imperfect machine (quad misalignments + BPM errors) restores polarization levels.

45 GeV

Oide optics with $Q_x=0.1$, $Q_y=0.2$, $Q_\phi=0.05$

Excellent polarization at the Z (but slow)

Polarization [%]

Energy spread increases $\sigma_{Eb} \propto E_b^{3/2}/\rho$ and polarization level decreases.

At the W expectation similar to LEP at Z

$\Rightarrow$ enough for energy calibration

80 GeV

Machine with imperfections after correction

Linear SITROS

Minimum polarization level required

E. Gianfelice-Wendt

M. Koratzinos, IAS2018, HKUST, Hong Kong, 22 January 2018.
At the Z peak we collect $10^6 \mu\mu$ events every 5 minutes. Their kinematics is affected by:
- energy spread
- $e^+$ vs $e^-$ energy difference.

P. Janot has shown that indeed both can be determined with extremely good precision with these events.

The energy difference is an important ingredient in understanding the RF model.
A note on attainable precision

Example: the W mass

Prediction:

\[
m_W = 80.3593 \pm 0.0001 (m_{\text{top}}) \pm 0.0001 (m_Z) \pm 0.0002 (\alpha_S) \pm 0.0003 (\alpha_{\text{QED}}) \pm 0.0003 (m_H) \pm 0.0040 \text{(theo.)}
\]

before FCC

After FCC

\[
m_W = 80.3593 \pm 0.0001 (m_{\text{top}}) \pm 0.0001 (m_Z) \pm 0.0002 (\alpha_S) \pm 0.0003 (\alpha_{\text{QED}}) \pm 0.0003 (m_H) \pm 0.0040 \text{(theo.)}
\]

direct measurement:

\[
m_W = 80.385 \pm 0.0005
\]

If only one ingredient is missing, the sensitivity to new physics may entirely vanish

Essential to reduce theory error: necessitates calculation up to 3-4 loops.
Effort has already started. 2 loop calculations finished – 3 loops started.
Workshop at CERN 12-13 January 2018 to kickstart this