Physics at FCC-ee

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on behalf of the FCC-ee study group

Outline

1. The Future Circular Collider Study
2. FCC-ee Electroweak Studies at the Z Pole, ZH, W⁺W⁻ and t¯t thresholds
3. QCD Physics at FCC-ee
FCC – Future Circular Collider

FCC - international collaboration hosted at CERN, goal: construction of ~100 km circumference tunnel infrastructure in Geneva area
to host:

✓ $e^-e^+$ collider: FCC-ee – potential first step, preceding the FCC-pp
✓ p-p collider: FCC-hh – flagship, 100 TeV p-p, 16T Nb$_3$Sn magnets
✓ e-p collider: FCC-he – additional option of e-p collisions; e$^-$ from ERL

The Conceptual Design Report issued in January, 2019:
(~1364 contributors, 351 institutes – a truly global collaboration and effort – as suggested by the EPPSU'13):
https://fcc-cdr.web.cern.ch/

The FCC-ee European Particle Physics Strategy Update (EPPSU) document:
https://cds.cern.ch/record/2653669

FCC week 2019, Brussels, 24-28, June

https://fcc-web.cern.ch/

https://cds.cern.ch/record/2653669

https://fcc-week2019.web.cern.ch/
The FCC project plan is fully integrated with HL-LHC exploitation and provides for seamless further continuation of particle physics in Europe.
# FCC-ee Operation Model

<table>
<thead>
<tr>
<th>working point</th>
<th>Design luminosity/IP [10^{34} cm^{-2}s^{-1}]</th>
<th>total luminosity (2 IPs)/ yr</th>
<th>physics goal</th>
<th>run time [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z first 2 years</td>
<td>115 (50% nominal)</td>
<td>24 ab^{-1}/year</td>
<td>150 ab^{-1}</td>
<td>4</td>
</tr>
<tr>
<td>Z later</td>
<td>230</td>
<td>48 ab^{-1}/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>28</td>
<td>6 ab^{-1}/year</td>
<td>10 ab^{-1}</td>
<td>2</td>
</tr>
<tr>
<td>H</td>
<td>8.5</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**

**Total program duration: 15 years (including machine modifications)**

- **Phase 1 (Z, W, H): 9 years,**
- **Phase 2 (top): 6 years**

(Total luminosity calculation based on 185 physics days per year, 75% efficiency, design luminosities and 10% overall contingency)
FCC-ee Collider Parameters

- Two rings (separate for $e^+$ and $e^-$); two interaction points (3 & 4 IPs under study), flat beams with very strong focusing ($\beta^* y \approx 1\text{mm}$); top-up injection (booster), crab waist crossing optics, non-zero (30 mrad) crossing angle; $P_{SR} = 100$ MW, four working points:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\sqrt{s} = M_Z$</th>
<th>$\sqrt{s} = M(WW)$</th>
<th>$\sqrt{s} = M(ZH)$</th>
<th>$\sqrt{s} = M(t\bar{t})$</th>
<th>LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{beam}$ [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>175 - 182.5</td>
<td>104.5</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>5.4</td>
<td>4</td>
</tr>
<tr>
<td>No. Bunches/beam</td>
<td>16 640</td>
<td>2 000</td>
<td>393</td>
<td>48</td>
<td>4</td>
</tr>
<tr>
<td>SR energy loss/turn [GeV]</td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
<td>9.21</td>
<td>3.34</td>
</tr>
<tr>
<td>SR power [MW]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>22</td>
</tr>
<tr>
<td>SR energy loss/turn [GeV]</td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
<td>9.21</td>
<td>3.4</td>
</tr>
<tr>
<td>RF Voltage [GV]</td>
<td>0.1</td>
<td>0.44</td>
<td>2.0</td>
<td>10.9</td>
<td>3.5</td>
</tr>
<tr>
<td>$\beta^*_x$ [m]</td>
<td>0.15</td>
<td>0.2</td>
<td>0.3</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>$\beta^*_y$ [mm]</td>
<td>0.8</td>
<td>1</td>
<td>1</td>
<td>1.6</td>
<td>50</td>
</tr>
<tr>
<td>$\epsilon_x$ [nm]</td>
<td>0.27</td>
<td>0.28</td>
<td>0.63</td>
<td>1.46</td>
<td>19.3</td>
</tr>
<tr>
<td>$\epsilon_y$ [pm]</td>
<td>1</td>
<td>1.7</td>
<td>1.3</td>
<td>2.9</td>
<td>230</td>
</tr>
<tr>
<td>$L,(10^{34} \text{ cm}^{-2}\text{s}^{-1})$/IP</td>
<td>230</td>
<td>28</td>
<td>8.5</td>
<td>1.55</td>
<td>0.012</td>
</tr>
<tr>
<td>Statistics (2expts)</td>
<td>5x10^{12} Z / 6yrs</td>
<td>3x10^7 WW/2yr</td>
<td>10^6 ZH/5yrs</td>
<td>10^6 $t\bar{t}$ / 5yrs</td>
<td></td>
</tr>
</tbody>
</table>

LEP1: $2.1 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$
LEP2: $3.6 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$
### Event statistics:

<table>
<thead>
<tr>
<th>Event Type</th>
<th>$E_{cm}$ (GeV)</th>
<th>$N_{e^+e^-}$</th>
<th>Reaction</th>
<th>Luminosity Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z peak</td>
<td>91</td>
<td>$5 \times 10^{12}$</td>
<td>$e^+e^- \rightarrow Z$</td>
<td>LEP x $10^5$</td>
</tr>
<tr>
<td>WW threshold</td>
<td>161</td>
<td>$3 \times 10^7$</td>
<td>$e^+e^- \rightarrow WW$</td>
<td>LEP x $10^3$</td>
</tr>
<tr>
<td>ZH threshold</td>
<td>240</td>
<td>$10^6$</td>
<td>$e^+e^- \rightarrow ZH$</td>
<td>Never done</td>
</tr>
<tr>
<td>tt threshold</td>
<td>350</td>
<td>$10^6$</td>
<td>$e^+e^- \rightarrow t\bar{t}$</td>
<td>Never done</td>
</tr>
</tbody>
</table>

### FCC-ee Collider Parameters

**Luminosity per facility**

- $L \propto P_{synrad} E_{cm}^{-3.5}$
- $\sqrt{s}$ [GeV]
- $L \propto P_{RF} E_{cm}$

### Errors

- Z
- WW
- ZH
- $t\bar{t}$

- ECM errors:
  - 100 keV
  - 300 keV
  - 5 MeV
  - 10 MeV

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C. Biscari ESSP, Granada, May 2019
FCC-ee Detectors: CLD

CLD - detector model for FCC-ee derived from CLICdp model and optimized for FCC-ee experimental conditions

- **Full silicon tracking system** (≥12 hits/track)
- **High granularity calorimeters optimized for particle flow reconstruction**
- **Superconducting coil (2T) located outside the calorimeters**
- **Steel return yoke containing muon chambers**
- **Forward region reserved for Machine-Detector Interface and LumiCal**
- Tracking fully efficient from 700 MeV
- $\delta pT \approx 4 \times 10^{-5} \text{ GeV}^{-1}$ (for muons $p=100$ GeV)
- $\Delta E/E = (3-5)\%$ (barrel region)
- Efficiency for electrons and gammas > 95%
FCC-ee Detectors: IDEA

IDEA – new, innovative, possibly more cost-effective design

- **Silicon vertex detector**
  (5 layers of pixels (MAPS) 30x30 µm$^2$, point resolution of 5 µm)

- **Short-drift, ultra light wire chamber**
  (90%/10% He/iC$_4$H$_{10}$, momentum resolution 0.25%, impact parameter resolution 4 µm)

- **Dual-readout calorimeter**
  (scintillating fibers sensitive to all charged particles, clear fibers sensitive only to Cherenkov light; $\sigma_E = \frac{11\%}{\sqrt{E}} + 1\%$

- **Thin and light solenoid coil inside calorimetric system**
  (2T, stored energy 170 MJ)
The ZH threshold never studied in e⁺e⁻  

**FCC-ee**  

\[ N_{ZH} \sim 10^6 \]

- The Higgs production measured inclusively from its presence as a recoil to the Z in the process e⁺e⁻ → ZH  
  \[ m_{\text{recoil}}^2 = (\sqrt{s} - E_Z)^2 - p_Z^2 \]
- \[ \Delta m_H = 10 \text{ MeV} \]
- Absolute measurement of the \( g_{HZZ} \rightarrow \Gamma_H \rightarrow \) other couplings \( g_{ZXX} \)  
  \( X = b, c, \tau, \mu, W, g, \gamma, \ldots \)

- The couplings of the 3rd and 2nd generation fermions accessible  
  (most with sub-percent precision)
- This precision yields the New Physics (NP) sensitivity ~10 TeV
- A possible pattern of deviations can discriminate between different BSM models
- See the talks: *Higgs measurements at the FCC-ee*  
  *(abstract 280)*  

*Global EFT fits from Higgs at the FCC-ee*  
*(abstract 283)*
FCC-ee Electroweak Physics at the Z Pole

- Z pole scan:
- Beam energy calibration is crucial
- Precision limited by beam energy calibration and theoretical uncertainties

The direct measurement of $\alpha_{\text{QED}}(m_Z^2)$ from the muon FB asymmetry just below and just above the Z pole (as part of Z resonance scan – no need of extrapolation from $\alpha_{\text{QED}}(0)$)

See the talk „Electroweak physics at FCC-ee“ (abstract 281)

P. Janot JHEP 02 (2016) 053
**FCC-ee Top and W Physics**

The WW threshold scan

**LEP**

\[ N_{WW} = 1.1 \times 10^4 \]

**FCC-ee**

\[ N_{WW} \sim 3 \times 10^7 \]

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**The WW threshold scan**

<table>
<thead>
<tr>
<th>Observable</th>
<th>present value ± error</th>
<th>FCC – ee Stat.</th>
<th>FCC – ee Syst.</th>
<th>Improvement factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_W ) [MeV/c^2]</td>
<td>( 80379 \pm 12 )</td>
<td>0.6</td>
<td>0.3</td>
<td>18</td>
</tr>
<tr>
<td>( \Gamma_W ) [MeV]</td>
<td>( 2085 \pm 42 )</td>
<td>1.5</td>
<td>0.3</td>
<td>27</td>
</tr>
</tbody>
</table>

See the talk "Electroweak physics at FCC-ee" *(abstract 281)*

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The t-bar threshold never studied in e^+e^-

**FCC-ee**

\[ N_{tt} \sim 10^6 \]

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<table>
<thead>
<tr>
<th>Observable</th>
<th>present value ± error</th>
<th>FCC – ee Stat.</th>
<th>FCC – ee Syst.</th>
<th>Improvement factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_t ) [MeV/c^2]</td>
<td>( 172900 \pm 400 )</td>
<td>20</td>
<td>small</td>
<td>20</td>
</tr>
<tr>
<td>( \Gamma_t ) [MeV]</td>
<td>( 1420 \pm 190 )</td>
<td>40</td>
<td>small</td>
<td>5</td>
</tr>
</tbody>
</table>

See the talk "Top quark physics at the FCC-ee" *(abstract 284)*
Assets of QCD Studies in $e^+e^-$ Collisions

- Extremely clean environment
- Fully controlled QED initial-state with known kinematics
- Controlled QCD radiation - only from the final state
- Well defined quark, gluon and heavy-quark jets
- Relatively small non-perturbative QCD uncertainties (lack of QCD underlying event, no PDFs....)
- Fragmentation and hadronization - direct and clean
- Large statistical samples
- Studies of $\gamma\gamma$ SM and BSM collisions (in Equivalent Photon Approximation (EPA))
- ...

David d'Enterria
Reminder: QCD Studies at LEP

✓ The successful running of LEP yielded a crucial impact on the understanding of QCD (~240 publications)

✓ The QCD highlights from LEP:
  - Studies of hadronic event shapes
  - Measurements of $\alpha_s$
  - Determinations of QCD colour factors and tests of the non-Abelian gauge structure of QCD
  - Studies of differences between quark and gluon jets
  - Tests of Monte Carlo shower and hadronization models
  - Studies of QCD with heavy quarks
  - Advances in two-photon scattering processes
  - ...

<table>
<thead>
<tr>
<th>No. of hadronic events</th>
<th>LEP</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} \sim 91$ GeV</td>
<td>$10^7$</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>$\sqrt{s} \sim 160$ GeV</td>
<td>$10^4$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$\sqrt{s} \sim 240$ GeV</td>
<td>-</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>
The QCD Objectives of FCC-ee

✓ **High precision $\alpha_s$ determination** (with the accuracy at the $\%$ level) from
  - hadronic $\tau$ decays
  - Jet rates, event shapes
  - hadronic Z decays
  - hadronic W decays

✓ **High precision studies of perturbative parton radiation** including:
  - jet rates and event shapes
  - jet substructure,
  - quark/gluon/heavy-quark discrimination
  - $g,q,b,c$ parton-to-hadron fragmentation functions

✓ **High precision non-perturbative QCD studies** including:
  - colour reconnection
  - final-state multiparticle correlations

✓ **High precision hadronization studies**
  - very rare hadron production and decays
The QCD Coupling Constant $\alpha_s$ at FCC-ee

- The $\alpha_s$ determines the strength of the strong interaction at a given scale.
- The unique free parameter of QCD in the limit $m_q \to 0$.

- The $\alpha_s$ is the least precisely measured of all four couplings of fundamental interactions:
  - $\Delta \alpha \sim 10^{-10}$
  - $\Delta G_F \sim 10^{-7}$
  - $\Delta G \sim 10^{-5}$
  - $\Delta \alpha_s \sim 10^{-2}$

- The $\alpha_s$ is determined by comparing now 6 groups of experimental observables to pQCD NNLO and N$^3$LO predictions.
- The global average is provided at the Z pole.

- Huge statistics of hadronic $\tau$, W and Z decays.
- N$^3$L0 perturbative QCD calculations.

- $\Delta \alpha_s \sim 10^{-3}$
The QCD Coupling Constant $\alpha_s$ at FCC-ee

**τ decays:** The relevant quantity: computable at $N^3$LO:

$$R_\tau = S_{\text{EWNC}} \left( 1 + \sum_{n=1}^{4} c_n (\frac{\alpha_s}{\pi})^n + O(\alpha_s^5) + \delta_{\text{np}} \right)$$

The current experimental value:

$$R_{\tau,\text{exp}} = 3.4697 \pm 0.0080 \text{ (±0.23%)}$$

The current determination of the $\alpha_s$:

$$\alpha_s(m_Z) = 0.1192 \pm 0.0018 \text{ (±1.5%)}$$

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**The event shapes,** like e.g. thrust ($T$), C-parameter...

$$T = \max_i \left( \frac{\sum_{i=1}^{n} |\vec{p}_i \cdot \vec{n}|}{\sum_{i=1}^{n} |\vec{p}_i|} \right)$$

$$C = \frac{3}{2} \frac{\sum_{i,j=1}^{n} |\vec{p}_i||\vec{p}_j| \sin^2 \theta_{ij}}{\left( \sum_{i=1}^{n} |\vec{p}_i| \right)^2}$$

**and N jet cross sections** are computed at $N^{2,3}$LO+$N^2$LL accuracy

The current combination of LEP results yields

$$\frac{\delta \alpha_s(m_Z)}{\alpha_s(m_Z)} < 2.9\%$$

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**FCC-ee**

$N(Z \to \tau^+\tau^-) \sim 10^{11}$ & theoretical progress

$\delta \alpha_s(m_Z)/\alpha_s(m_Z) < 1\%$

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$N(Z \to \text{hadrons}) \sim 10^{12}$ & theoretical progress

$\delta \alpha_s(m_Z)/\alpha_s(m_Z) < 1\%$
The QCD Coupling Constant $\alpha_S$ at FCC-ee

Hadronic $Z$ decays:

- At LEP, the $\alpha_S$ was extracted from the fits to the three $Z$-peak observables:
  
  $$\sigma_l^0 = \frac{12\pi}{m_Z} \frac{\Gamma_l^2}{\Gamma_Z^2}$$
  $$\sigma_{\text{had}}^0 = \frac{12\pi}{m_Z} \frac{\Gamma_{\text{had}}}{\Gamma_Z^2}$$
  $$R_l^0 = \frac{\Gamma(Z \rightarrow \text{had})}{\Gamma(Z \rightarrow l)} = \frac{\Gamma_{\text{had}}}{\Gamma_l}$$

- Computable at N$^3$LO:
  
  $$R_l^0 = R_Z^{\text{EW}} N_C (1 + \sum_{n=1}^{4} c_n \left( \frac{\alpha_S}{\pi} \right)^n + \mathcal{O}(\alpha_S^5) + \delta_m + \delta_{\text{np}})$$

- The current $\alpha_S$ value:
  
  $$\alpha_S(m_Z) = 0.1196 \pm 0.0030 \quad (\pm 2.5\%)$$

- With the Higgs boson observation, the $\alpha_S$ can be also directly extracted from the full SM fit.

- And theoretical progress:
  
  $$\delta \alpha_S(m_Z) / \alpha_S(m_Z) < 0.2\%$$

FCC-ee $N_Z \sim 5 \times 10^{12}$
The QCD Coupling Constant $\alpha_S$ at FCC-ee

**Hadronic W decays:**

- The observable: ratio of hadronic to leptonic W decay widths

$$\Gamma_{W,\text{had}} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks } i,j} |V_{i,j}|^2 \left[ 1 + \sum_{k=1}^4 \left( \frac{\alpha_S}{\pi} \right)^k + \delta_{\text{EW}}(\alpha_{\text{QED}}) + \delta_{\text{mixed}}(\alpha_{\text{QED}} \alpha_S) \right]$$

  - [EWK: -0.35%]

- Computable at $N^{2,3}\text{LO}$:
  - $|V_{i,j}|^2$: 96.60%
  - $\alpha_S^{(1\text{-LO})}$: 3.78%
  - $\alpha_S$: -0.05%

- The LEP $\alpha_S$ value: $\alpha_S(m_Z) = 0.117 \pm 0.040$ ($\pm 35\%$)

**FCC-ee** $N_{WW} \sim 3 \times 10^7$ 

$$\delta \alpha_S(m_Z)/\alpha_S(m_Z) < 0.3\%$$

and theoretical progress

The precision on $\alpha_S$ influences all QCD cross-sections and decays...

<table>
<thead>
<tr>
<th>Quantity</th>
<th>FCC-ee</th>
<th>future param.unc.</th>
<th>Main source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_Z$ [MeV]</td>
<td>0.1</td>
<td>0.1</td>
<td>$\delta \alpha_S$</td>
</tr>
<tr>
<td>$R_b$ [$10^{-5}$]</td>
<td>6</td>
<td>&lt; 1</td>
<td>$\delta \alpha_S$</td>
</tr>
<tr>
<td>$R_\ell$ [$10^{-3}$]</td>
<td>1</td>
<td>1.3</td>
<td>$\delta \alpha_S$</td>
</tr>
</tbody>
</table>

David d’Enterria, FCC Phys. Workshop, CERN, Jan 2018
Jet rates are expected to be measured with the accuracy $10^{-6}$ (at the Z pole), including:

| Rate of    | up to $k_T$ [GeV] | $|\ln(y)|$ |
|-----------|-------------------|----------|
| 4-jet events | $\sim 30$         | $\sim 2$ |
| 5-jet events | $\sim 20$         | $\sim 3$ |
| 6-jet events | $\sim 12$         | $\sim 4$ |
| 7-jet events | $\sim 7.5$        | $\sim 5$ |

(jet resolution parameter: $y = \frac{k_T^2}{s}$)

Comparison with theoretical calculations with accuracy beyond the NNLO+NNLL ($\rightarrow \alpha_s$ extraction)

Event shapes are affected by logarithmic enhancements (resummed up to $N^3$LL: pQCD, SCET,...) and hadronization corrections (estimated from MC generators)

The FCC-ee operating at different CM energies will provide much tighter control on resummation and hadronization effects in event shape distributions

$\sqrt{s} = 91.2$ GeV $\rightarrow$ non-perturbative uncertainties reduced from 9% to 2%
Goal: parton flavour discrimination (PFD): quark – gluon; (u,d,s) – c – b
Such separation crucial for precision SM measurements and BSM searches
The PFD is based on the comparison of jet substructure properties to MC predictions
Quark-gluon PFD at LEP: studies of $Z \rightarrow b\bar{b}g$ (statistically limited)

- $10^5$ more Zs
- a unique sample of $10^4$ $H \rightarrow gg$ events - FCC-ee as a „pure gluon” factory

The current level of discrepancies between MC generators (hadron level distributions):

The generalized angularities:

$$\lambda^\kappa_\beta = \sum_{i \in \text{jet}} Z^\kappa_i \theta^\beta_i$$

$Z_i$ – the momentum fraction of particle i
$\Theta_i$ – the angular fraction of part. i w.r.t. the jet radius

Significant variations between generators for gluon distributions
new insight from the FCC-ee

: large samples of top, W, Z, H decays to b and c quarks; important progress in heavy-quark fragmentation and in gluon fragmentation $g \rightarrow b\bar{b}$ (cc)
The uncertainties due to non-perturbative QCD effects (colour reconnection, hadronization, final state interactions...) impact many high-precision SM studies. e^+e^- collisions offer favourable conditions to control them.

**Colour Reconnection (CR):**

- Strong interaction (colour flow) between colour singlet parton systems of different origin.
- LEP2: exclusion (99.5% CL) of the no-CR null hypothesis but statistics insufficient for more quantitative results.

**FCC-ee:** $\Delta m_W \sim 1$ MeV (threshold scan) & the $3 \times 10^3$ gain in the number of WW pairs.

The shift in the reconstructed $m_W$ expected from different PYTHIA 8 CR models:

<table>
<thead>
<tr>
<th>$E_{cm}$ (GeV)</th>
<th>$\langle \delta m_W \rangle$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td>170</td>
<td>18</td>
</tr>
<tr>
<td>240</td>
<td>95</td>
</tr>
<tr>
<td>350</td>
<td>72</td>
</tr>
</tbody>
</table>

Discrimination between CR models.
Parton Hadronization (PH) – phenomenological models – MC generators

The understanding of many aspects of PH like

- baryon production
- strangeness production
- final state correlations
- colour string dynamics
- ...

can profit significantly from the FCC-ee (hadronic) data samples:

- large statistics
- excellent tracking and calorimetry
- efficient hadron identification
- ...

Ξ- spectra measured by ALEPH and CMS, compared to the predictions from modern event generators
The FCC-ee project aims at collection of huge data samples at the four relevant working points: Z-pole, ZH, WW and ttbar thresholds.

The uncertainties of the most important electroweak observables are expected to be improved by a factor of at least 10.

The QCD program of the FCC-ee encompasses:

- High precision $\alpha_s$ determination
- High precision studies of perturbative parton radiation
- High precision non-perturbative QCD studies
- High precision hadronization studies
EU H2020 Design Study
EuroCirCol

European Union Horizon 2020 program:

• 3 MEURO co-funding
• Started June 2015, ends in Dec 2019
• 15 European beneficiaries & KEK & associated FNAL, BNL, LBL, NHFML

Covers FCC-hh key work packages:

• Optics design (arc & IR)
• Cryogenic beam vacuum system design including beam tests at ANKA
• 16 T dipole design, construction folder for demonstrator magnets
European Advanced Superconductivity Innovation and Training Network

Funding 15 Early Stage Researchers over 3 years & training in key areas

- SC wires at low temperatures for magnets (Nb$_3$Sn, MgB$_2$, HTS)
- Superconducting thin films for RF and beam screen (Nb$_3$Sn, Tl)
- Electrohydraulic forming for RF structures
- Turbocompressor for Nelium refrigeration
- Magnet cooling architectures

- started 1 October 2017
double ring $e^+e^-$ collider ~100 km
follows footprint of FCC-hh, except around IPs
asymmetric IR layout & optics to limit synchrotron radiation towards the detector
presently 2 IPs (alternative layouts with 3 or 4 IPs under study), large horizontal crossing angle 30 mrad, crab-waist optics
synchrotron radiation power 50 MW/beam at all beam energies; tapering of arc magnet strengths to match local energy
top-up injection scheme; requires booster synchrotron in collider tunnel
FCC-ee luminosity versus energy

luminosity $[10^{34} \text{ cm}^{-2}\text{s}^{-1}]$ (2 IPs)

- Z $91$ GeV
- WW $160$ GeV
- ZH $240$ GeV
- ttbar $350-365$ GeV

H s-channel
figure of merit for lepton colliders

FCC-ee: most efficient from Z to $t\bar{t}$

E. Jensen, EPPSU symposium, Granada
FCC-ee: a sustainable accelerator

Electricity cost ~200 euro per Higgs boson

Luminosity per wall plug power $\left[ 10^{34} \text{ cm}^{-2}\text{s}^{-1}/100 \text{ MW} \right]$

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

![Graph showing luminosity per wall plug power vs. c.m. energy (GeV).](image)
Tunnel integration in arcs

FCC-ee

FCC-hh

5.5 m inner diameter
FCC-ee reaches highest luminosities & energies by combining ingredients and well-proven concepts of several recent colliders:

**B-factories:** KEKB & PEP-II: double-ring lepton colliders, high beam currents, top-up injection

**DAFNE:** crab waist, double ring

**Super B-fact., S-KEKB:** low $\beta_y^*$

**LEP** high energy, SR effects

**VEPP-4M, LEP:** precision E calibration

**KEKB:** $e^+$ source

**HERA, LEP, RHIC:** spin gymnastics
Construction cost phase 1 (FCC-ee) is 11.6 BCHF
- 5.4 BCHF for civil engineering (47%)
- 2.2 BCHF for technical infrastructure (19%)
- 4.0 BCHF accelerator and injector (34%)

Construction cost phase 2 (FCC-hh) is 17.0 BCHF.
- 13.6 BCHF accelerator and injector (57%)
  - Major part for 4,700 Nb₃Sn 16 T main dipole magnets, totalling 9.4 BCHF, targeting 2 MCHF/magnet.
- CE and TI from FCC-ee re-used, 0.6 BCHF for adaptation
- 2.8 BCHF for additional TI, driven by cryogenics (Cost FCC-hh stand alone would be 24.0 BCHF.)
The recoil technique in $e^+e^- \rightarrow ZH$ - unique for lepton colliders:

- Look just at the Z and reconstruct its decay products
- ZH events are tagged independently of Higgs decay mode (include invisible decay modes)
- Very clean Higgs mass determination:
  \[ m_{\text{recoil}}^2 = (\sqrt{s} - E_{\text{ll}})^2 - |\vec{p}_{\text{ll}}|^2 \]
  \[ \Delta m_H \sim 10 \text{ MeV} \]
- Precise determination of the ZH cross-section:
  \[ \Delta \sigma(ZH)/\sigma(ZH) \sim 0.5\% \]
- Precise measurement of the H-Z-Z coupling ($g_{HZZ}$):
  \[ \sigma(HZ) \propto g_{HZZ}^2 \]
Determination of the H-W-W coupling ($g_{HWW}$): 
- Measure the rate of WW Fusion to HZ processes – preferably at 350 GeV, using Higgs decays to the given final state e.g.

\[
\frac{\sigma(e^+e^- \rightarrow H\nu_e\bar{\nu}_e) \times BR(H \rightarrow b\bar{b})}{\sigma(e^+e^- \rightarrow HZ) \times BR(H \rightarrow b\bar{b})} \propto \frac{g_{HWW}^2}{g_{HZZ}^2}
\]

$g_{HWW}$ measured

Determination of the Higgs total width ($\Gamma_H$):
1. Use the HZ process and $H \rightarrow ZZ^*$

\[
\sigma(e^+e^- \rightarrow HZ) \times BR(H \rightarrow ZZ^*) \propto \frac{g_{HZZ}^4}{\Gamma_H}
\]

$\Gamma_H$ measured
2. Use the WW Fusion process and $H \rightarrow WW^*$:

\[
\sigma(e^+e^- \rightarrow H\nu_e\bar{\nu}_e) \times BR(H \rightarrow WW^*) \propto \frac{g_{HWW}^4}{\Gamma_H}
\]
Higgs Couplings: Post Factum

**ATLAS** Preliminary
\[ \sqrt{s} = 13 \text{ TeV}, \ 36.1 - 79.8 \text{ fb}^{-1} \]
\[ m_H = 125.09 \text{ GeV}, \ |y_H| < 2.5 \]

**LHC**

**CLICdp**
\[ \sqrt{s} = 350 \text{ GeV} + 1.4 \text{ TeV} + 3 \text{ TeV} \]

3rd generation only (qualitative precision level)

3rd AND 2nd generations accessible

\[ \Delta k_f \sim 15\% \quad \rightarrow \quad \Delta k_f \sim 1\% \]

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Normalized Higgs Couplings

- Higgs couplings normalized to the Standard Model predictions:
  \[ k_f = \frac{g_{Hff}}{g_{Hff}^{SM}}, \quad f = b, c, \tau \]
  \[ k_V = \frac{g_{HVV}}{g_{HVV}^{SM}}, \quad V = W, Z, \gamma, g \]

- Fingerprinting NP: different BSM models predict different pattern of deviations from the SM:
  
  [Graphs showing deviations from SM for Supersymmetry and Composite Higgs]

- [Citation: Phys Rev. D 97, 053003 (2018)]
Measurements of the Higgs self-coupling

- assuming all other couplings at MS, $\Delta \kappa_H/\kappa_\lambda \sim 12\%$ (9\% 4 I.P.)
- maximum sensitivity at the threshold production

- from a global EFT fit $\Delta \kappa_H/\kappa_\lambda \sim 25\%$ (4 IPs)
- changing CMS energy helps in reducing correlations
**WW Threshold Scan: the W Mass and Width**

- **The W mass from $\sigma_{WW}$:**
  
  Measure $\sigma_{WW}$ in two energy points $E_1$ and $E_2$, with the fractions of luminosity $f$ and $(1-f)$ for evaluation of both $m_W$ and $\Gamma_W$.

- **The W width from $\sigma_{WW}$:**
  
  - Measure $\sigma_{WW}$ in two energy points $E_1$ and $E_2$, with the fractions of luminosity $f$ and $(1-f)$ for evaluation of both $m_W$ and $\Gamma_W$.
  
  - Choose the parameters $E_1$, $E_2$ and $f$ in order to minimize the errors: $\Delta\Gamma_W$ and $\Delta m_W$.

- **TL Lesiak**
  
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**LEP**

- **Preliminary**

- **$\Delta m_W = (\frac{d\sigma}{dm_W})^{-1} \Delta \sigma$**

- **$\sqrt{s}$ [GeV]**

- **Values:**
  
  - $\Delta m_W = 1$ MeV
  
<table>
<thead>
<tr>
<th>$N_{WW}$</th>
<th>$M_W$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP2 Stat./Prec.</td>
<td>4 x 10^4</td>
</tr>
<tr>
<td>FCC – ee stat (syst)</td>
<td>3 x 10^7</td>
</tr>
<tr>
<td>80376 ± 33 ± 4</td>
<td>0.3 (&lt; ±1)</td>
</tr>
</tbody>
</table>

- **Paolo Azzurri**
  
  2nd FCC Physics workshop
W Physics: Branching Ratios, TGCs...

- **WW samples** (FCC-ee)
  - $\sqrt{s}$ [GeV]: 161, 240, 350
  - $N_{WW} \times 10^6$: 30, 80, 15

- **W Branching ratios (%)**
  - LEP2
    - $\text{BR}(W \rightarrow \ell \nu)$: 10.65 ± 0.17
    - $\text{BR}(W \rightarrow \mu \nu)$: 10.59 ± 0.15
    - $\text{BR}(W \rightarrow \tau \nu)$: 11.44 ± 0.22
    - $\text{BR}(W \rightarrow l \nu)$: 10.84 ± 0.09
    - $\text{BR}(W \rightarrow \text{hadrons})$: 67.48 ± 0.28
  - Lepton universality tested at 2% level (2.7σ discrepancy between τ and μ/e)
  - Quark-lepton universality tested at 0.6%

- **FCC-ee**
  - Lepton universality test at 0.04% level
  - Quark-lepton universality test at 0.01%
  - Flavour tagging \( V_{cs} V_{cb} \)

- **Triple Gauge Couplings**
  - Selected LEP limits (95% C.L.)
    - $\Delta k_\gamma$: $[-9.9, 6.6] \times 10^{-2}$
    - $\lambda_\gamma$: $[-5.9, 1.7] \times 10^{-2}$
    - $\Delta k_Z$: $[-7.4, 5.1] \times 10^{-2}$
    - $\lambda_z$: $[-5.9, 1.7] \times 10^{-2}$
    - $\Delta g_1$: $[-5.4, 2.1] \times 10^{-2}$
  - FCC-ee: overall improvements by a factor of 50 to compare with LEP

- **The strong coupling constant**
  - FCC-ee: $\Delta_{\text{rel}} \alpha_S(m_W^2) = 3 \times 10^{-3}$
  - LEP2 precision: 37%

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$m_W$ vs $m_t$
Electroweak Physics at the Z pole

**Z mass and width (from Z pole scan):**

The crucial factor: continuous $E_{\text{cm}}$ calibration (resonant depolarization)

$$\Delta E_{\text{CM}} \approx (10 \, \text{(stat)} + 100 \, \text{(syst)}) \, \text{keV}$$

<table>
<thead>
<tr>
<th>$Z$ mass</th>
<th>$1 \times 10^{-6}$</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$ width</td>
<td>$5 \times 10^{-5}$</td>
<td>20</td>
</tr>
</tbody>
</table>

$\sim 300 \, \text{(stat)} \oplus \sim 10 \, \text{(syst)}$

$2.1 \, \text{MeV} \rightarrow 100 \, \text{keV}$

$2.3 \, \text{MeV} \rightarrow 100 \, \text{keV}$

Normalized partial widths:

$$R_l = \frac{\Gamma_{\text{had}}}{\Gamma_{l\bar{l}}}, \quad l = e, \mu, \tau$$

$$\Gamma_{ff} \propto (g_V^f)^2 + (g_A^f)^2$$

$$R_q = \frac{\Gamma_{qq}}{\Gamma_{\text{had}}}, \quad q = b, c$$

necessary input for a precise measurement of EW couplings (next slide)

and $\alpha_s(m_Z^2)$ (from hadronic $Z$ decays). FCC-ee precision: $\Delta_{\text{rel}} \alpha_s(m_Z^2) = 2 \times 10^{-3}$

LEP: 2.5%
Electroweak Physics at the Z pole

Z asymmetries:

- $d\sigma_{ff}/d\cos{\theta} = \frac{3}{8} \sigma_{ff}^{\text{tot}} \left[(1 - P_e A_e)(1 + \cos^2{\theta}) + 2(A_e - P_e)A_f \cos{\theta}\right]$ 

  The forward-backward asymmetry:
  $A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4} A_e A_f$

  The left-right asymmetry:
  $A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = A_e$

$P_e$ - polarization of the initial state $e^-$

Experimentally accessible observables:

- $\mathcal{A}_f$ measured
- $g_V^f$, $g_A^f$ extracted

- $\sin^2{\theta_{W,\text{eff}}} = \frac{1}{4} \left(1 - \frac{g_V^f}{g_A^f}\right)$

- $\mathcal{A}_e \text{ measured}$

- $g_V^e$, $g_A^e$ extracted

- $\sin^2{\theta_{W,\text{eff}}} = \frac{1}{4} \left(1 - \frac{g_V^e}{g_A^e}\right)$

- $\mathcal{A}_\mu \text{ measured}$

- $g_V^\mu$, $g_A^\mu$ extracted

- $\sin^2{\theta_{W,\text{eff}}} = \frac{1}{4} \left(1 - \frac{g_V^\mu}{g_A^\mu}\right)$

- $\mathcal{A}_\tau \text{ measured}$

- $g_V^\tau$, $g_A^\tau$ extracted

- $\sin^2{\theta_{W,\text{eff}}} = \frac{1}{4} \left(1 - \frac{g_V^\tau}{g_A^\tau}\right)$

Precision on vector and axial couplings from $R_f$ and $A_f$:

- Improvement w.r.t. LEP: 10-100

Systematic uncertainties dominate

<table>
<thead>
<tr>
<th>fermion</th>
<th>$\Delta g_V$</th>
<th>$\Delta g_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>$2.5 \times 10^{-4}$</td>
<td>$1.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$2.0 \times 10^{-4}$</td>
<td>$2.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$3.5 \times 10^{-4}$</td>
<td>$0.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>$b$</td>
<td>$1.0 \times 10^{-2}$</td>
<td>$1.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$c$</td>
<td>$1.0 \times 10^{-2}$</td>
<td>$2.0 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Measurement of $\alpha_{\text{QED}}(m_Z^2)$ - better precision necessary for future precision SM tests!

- Current uncertainty: $\Delta \alpha_{\text{QED}}(m_Z^2) = 10^{-4}$

  from running coupling constant formula:

  $\alpha_{\text{QED}}(m_Z^2) = \frac{\alpha_{\text{QED}}(0)}{1 - \Delta \alpha_{\text{QED}}(m_Z^2) - \Delta \alpha_{\text{had}}(m_Z^2)}$

  dominated by the experimental determination of the hadronic vacuum polarization, obtained from dispersion integral with expt. input from low energies (KLOE, Belle, BaBar, CLEO, BES CMD-2...)

Alternative: the direct measurement of $\alpha_{\text{QED}}(m_Z^2)$ from the muon FB asymmetry just below and just above the Z pole (as part of Z resonance scan) – no need of extrapolation from $\alpha_{\text{QED}}(0)$

- The $A_{\text{FB}}^{\mu\mu}$ - self normalized quantity

  (no need for measurement of $L_{\text{int}}$)

  most uncertainties (sel. efficiency, det. acceptance) cancel in the ratio

  \[
  \frac{\Delta \alpha_{\text{QED}}}{\alpha_{\text{QED}}} \approx \frac{\Delta A_{\text{FB}}^{\mu\mu}}{A_{\text{FB}}^{\mu\mu}} \times \frac{Z + G}{Z - G}
  \]

  $Z(G)$ - Z(photon)-exchange terms

  Optimal CMS energies:

  - $\sqrt{s_-} = 87.9$ GeV
  - $\sqrt{s_+} = 94.3$ GeV

  \[
  \frac{1}{\alpha_{\text{QED}}(m_Z^2)} = \frac{1}{\alpha_\pm} + \beta_{\text{QED}} \log \frac{s_\pm}{m_Z^2}
  \]

  $\Delta \alpha_{\text{QED}}(m_Z^2) = 3 \times 10^{-5}$

  (adequate for future precision EW fits)

\[\sin^2 \theta_{\text{W,eff}}\] (absolute) uncertainties:

<table>
<thead>
<tr>
<th>Source</th>
<th>stat</th>
<th>syst</th>
<th>Improvement w.r.t. LEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>from muon FB</td>
<td>$10^{-7}$</td>
<td>$5.0 \times 10^{-6}$</td>
<td>100</td>
</tr>
<tr>
<td>from tau pol</td>
<td>$10^{-7}$</td>
<td>$6.6 \times 10^{-6}$</td>
<td>75</td>
</tr>
</tbody>
</table>

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The Z Invisible Width
– Number of Light Neutrino Species

1) $N_{\nu}$ determined at LEP1 from the Z line-shape scan:

$$N_{\nu} = 2.991 \pm 0.007$$

$$N_{\nu} \cdot \Gamma_{\nu} = \Gamma_{Z} - \Gamma_{h} - 3\Gamma_{l}$$

Only small room for improvements:
precision limited mainly by the theoretical uncertainty on luminosity determination
i.e. on small angle Bhabha cross section
(LEP1: $\Delta L/L = 0.00061, \, \Delta N_{\nu}^{lumi} = 0.0046 \, \Rightarrow \, \Delta N_{\nu}^{lumi} = 0.0001 \, @\, FCC-ee$).

$$\Delta N_{\nu}^{FCC-ee} = 0.00008(\text{stat}) \pm 0.0001(\text{syst})$$

2) $N_{\nu}$ from the radiative return process

Monophoton events (normalized to photon-lepton-lepton events):

$$e^+e^- \rightarrow Z \gamma, \, Z \rightarrow \nu\bar{\nu}$$

- LEP1: $N_{\nu} = 2.92 \pm 0.05$ (statistics too scarce).
- Photon selection common for both final states $\Rightarrow$ cancellations of systematics.
- $N_{\nu}$ can be measured vs $\sqrt{s}$ $\Rightarrow$ sensitivity to NP at high energy scales.
- FCC-ee sensitivity:

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [GeV]</th>
<th>years of running</th>
<th>$\Delta N_{\nu}$ (stat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>161</td>
<td>1</td>
<td>0.0011</td>
</tr>
<tr>
<td>240 &amp; 340</td>
<td>5</td>
<td>0.0008</td>
</tr>
<tr>
<td>125</td>
<td>1</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

$\Delta N_{\nu} \leq 4 \times 10^{-4}$ (running parasitically)
Sterile, right-handed neutrinos (N) are common in extensions of the SM; they couple to Higgs and SM ν

Substantial part of them are HNLs: very massive and characterised by macroscopic decay length

The HNL production and decay at the $\sqrt{s} = M_Z$

$\nu_L = \nu \cos \theta + N \sin \theta$

$\theta \approx m_\nu/m_N$

Experimental signatures

NC: 2 leptons/jets + $E_{\text{miss}}$
CC: 2 jets + lepton/$E_{\text{miss}}$

Search for (highly) displaced vertices; very clean events

FCC-ee sensitivity to HNLs up to $10^{-11}$

Complementary to beam dump facilities

The upper limits of LEP searches: $10^4$

A.Blondel et al., arXiv: 1411.5230 [hep-ex]
Flavour Physics

The sheer power of statistics:

<table>
<thead>
<tr>
<th>Particles</th>
<th>$B^0/B^+$</th>
<th>$B_s^0$</th>
<th>$\Lambda_b$</th>
<th>$B_c$</th>
<th>$Z \rightarrow \tau^+\tau^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yields (FCC-ee 150 $ab^{-1}$)</td>
<td>$10^{12}$</td>
<td>$2.5 \times 10^{11}$</td>
<td>$2.5 \times 10^{11}$</td>
<td>$2.5 \times 10^9$</td>
<td>$5.0 \times 10^{11}$</td>
</tr>
<tr>
<td>Yields (Belle II 50 $ab^{-1}$)</td>
<td>$10^{11}$</td>
<td>$10^7 - 8$</td>
<td>$-$</td>
<td>$-$</td>
<td>$5.0 \times 10^{10}$</td>
</tr>
</tbody>
</table>

LEP: $\sim 6 \times 10^6$

Example: $B \rightarrow K^*(892)\tau^+\tau^-$ decay

- Excellent vtx reconstruction ($\tau \rightarrow 3$ prongs)
- FCC-ee: 1000 signal events expected, Belle2: 10 events expected
- The amplitude analysis feasible

$10^{13}$ Z decays
ILD detector

Resolutions:
- Momentum: 10 MeV
- PV: 3 µm
- SV: 7 µm
- TV: 5 µm