Electroweak Physics at FCC-ee

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on behalf of the FCC-ee study group

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Outline

1. The Future Circular Collider Study
2. FCC-ee Electroweak Studies at the Z Pole
3. WW Physics at FCC-ee
FCC – Future Circular Collider

FCC - international collaboration hosted at CERN, goal: construction of ~100 km circumference tunnel infrastructure in Geveva 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 magnets
✓ e-p collider: FCC-he – additional option of e-p collisions; e- from ERL

„...the FCC offers a leap into completely uncharted territory, from delivering mind-boggling statistics of ~5 x 10^{12} Z decays (e^+ e^-), all the way up to proton-proton collision at an energy of 100 TeV."

CERN thinks bigger”, CERN Courier Magazine, June 2018

Short term goal: CDR and cost review by the end of 2018 to take part in discussion on European Strategy for Particle Physics 2020
**FCC-ee Collider Parameters**

- **FCC-ee**: two rings (separate for $e^+$ and $e^-$); four interaction points; flat beams with very strong focusing ($\beta^*_y \approx 1$ mm); top-up injection, crab waist crossing, non-zero crossing angle.

### 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>$E_{\text{beam}}$ [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>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>16640</td>
<td>2000</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>RF Voltage [GV]</td>
<td>0.1</td>
<td>0.44</td>
<td>2.0</td>
<td>10.93</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>$\varepsilon_x$ [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>$\varepsilon_y$ [pm]</td>
<td>1</td>
<td>1.7</td>
<td>1.3</td>
<td>2.9</td>
<td>230</td>
</tr>
<tr>
<td>$L \left(10^{34} \text{ cm}^{-2}\text{s}^{-1}\right)/\text{IP}$</td>
<td>&gt;200</td>
<td>&gt;25</td>
<td>&gt;7</td>
<td>&gt;1.4</td>
<td>0.012</td>
</tr>
<tr>
<td>Statistics (2expts)</td>
<td>5x$10^{12}$ Z / 6yrs</td>
<td>3x$10^7$ WW/2yr</td>
<td>$10^6$ ZH/5yrs</td>
<td>$10^6$ tt / 5yrs</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**

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

<table>
<thead>
<tr>
<th>Event</th>
<th>$E_{cm}$ [GeV]</th>
<th>$N_{events}$</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z peak</td>
<td>91</td>
<td>$5 \times 10^{12}$</td>
<td>$e^+e^- \rightarrow Z$</td>
</tr>
<tr>
<td>WW threshold</td>
<td>161</td>
<td>$3 \times 10^7$</td>
<td>$e^+e^- \rightarrow WW$</td>
</tr>
<tr>
<td>ZH threshold</td>
<td>240</td>
<td>$10^6$</td>
<td>$e^+e^- \rightarrow ZH$</td>
</tr>
<tr>
<td>tt threshold</td>
<td>350</td>
<td>$10^6$</td>
<td>$e^+e^- \rightarrow tt$</td>
</tr>
</tbody>
</table>

**Luminosities (10^{34} cm^{-2}s^{-1}):**

- **LEP1** $= 10^5$
- **LEP2** $= 10^3$
- **LEP3** $= Never done$
- **FCC-ee (Baseline, 2 IPs)** $= 10^5$
- **ILC (Baseline)** $= Never done$
- **CLIC (Baseline)** $= Never done$
- **CEPC (Baseline, 2 IPs)** $= Never done$

**Energy errors:**

- LEP: 100 keV
- LEP x 10^3: 300 keV
- Never done: 5 MeV
- Never done: 10 MeV
**FCC-ee Detectors**

- 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
- δpT ≈ 4 x 10^{-5} GeV^{-1} (for muons p=100 GeV)
- ΔE/E = (3-5)% (barrel region)
- Efficiency for electrons and gammas > 95%

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

**IDEA** - (International Detector Electron Accelerator) under development; drift chamber tracker
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, width</th>
<th>$\Delta_{\text{rel}}$ (LEP)</th>
<th>Improvement factor</th>
</tr>
</thead>
</table>
| $1 \times 10^{-6}$, $5 \times 10^{-5}$ | 20, 20 | 2.1 MeV $\rightarrow$ 100 keV, 2.3 MeV $\rightarrow$ 100 keV

- **Normalized partial widths:**
  - $R_l = \frac{\Gamma_{\text{had}}}{\Gamma_{\nu\bar{\nu}}}$, $l = e, \mu, \tau$
  - $R_q = \frac{\Gamma_{q\bar{q}}}{\Gamma_{\text{had}}}$, $q = b, c$
  - $\Gamma_{ff} \propto (g_V^f)^2 + (g_A^f)^2$
  - Necessary input for a precise measurement of EW couplings (next slide)

- **$\alpha_S(m_Z^2)$ (from hadronic Z decays):**
  - **FCC-ee precision:** $\Delta_{\text{rel}}\alpha_S(m_Z^2) = 2 \times 10^{-3}$
  - **LEP:** 2.5%

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Electroweak Physics at FCC-ee  
ICHEP 2018  
6. July 2018
Electroweak Physics at the Z pole

- **Z asymmetries:**

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

  - **Pe - polarization** of the initial state e-
  - 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:
    \[
    A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = A_e
    \]

  Experimentally accessible observables:

  - \( A_f \) measured (\( f = e, \mu, \tau, b, c \))
  - \( g^f_L, g^A_L \) extracted
  - \( \sin^2 \theta_{\text{w, eff}} = \frac{1}{4} \left( 1 - \frac{g^f_L}{g^A_L} \right) \)

  **Precision on vector and axial couplings from \( R_f \) and \( A_f \):**

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

<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>

**LEP & SLC:** longstanding discrepancies between different asymmetry measurements; uncertainties dominated by statistics
Electroweak Physics at the Z pole

- 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:
    - 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 $\alpha_{\text{QED}}(0)$
    - $A_{FB}^{\mu\mu}$ - self normalized quantity
      - no need for measurement of $L_{\text{int}}$; most uncertainties (sel. efficiency, det. Acceptance) cancel in the ratio
      - $\frac{\Delta \alpha_{\text{QED}}}{\alpha_{\text{QED}}} \sim \frac{\Delta A_{FB}^{\mu\mu}}{A_{FB}^{\mu\mu}} \times \frac{Z + \gamma}{Z - \gamma}$

Optimal CMS energies:
- $\sqrt{s_-} = 87.9$ GeV
- $\sqrt{s_+} = 94.3$ GeV

- $\frac{1}{\alpha_{\text{QED}}(m_Z^2)} = 1 + \beta_{\text{QED}} \log \frac{s_+}{m_Z^2}$
  - $\Delta \alpha_{\text{QED}}(m_Z^2) = 3 \times 10^{-5}$
  - (adequate for future precision EW fits)
The Z Invisible Width
– Number of Light Neutrino Species

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

$$N_\nu = 2.9840 \pm 0.0082$$

2σ below 3.0

A hint of non-unitarity of the PMNS matrix?

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

$$N_\nu = \frac{N_{\nu/e e^{-} \rightarrow \gamma Z_{\text{inv}}}^{\text{meas}}}{N_{\nu/e e^{-} \rightarrow \gamma Z_{\text{lept}}}^{\text{meas}}} \left( \frac{\Gamma_{\nu} \nu}{\Gamma_{\text{lept}}} \right)^{\text{SM}}$$

- 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>

$3 \times 10^7 \gamma Z(\text{inv})$ ev.

$\Delta N_\nu \leq 4 \times 10^{-4}$ (running parasitically)
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 $(1-f)$
- 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 $(1-f)$
  - 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 $\Delta m_W$:
  - $E_1 = 157.1 \text{ GeV}$
  - $E_1 = 162.3 \text{ GeV}$
  - $f = 0.4$
- $\Delta m_W = 1 \text{ MeV}$
- $\Delta \Gamma_W = 1.5 \text{ MeV}$
- $\Delta m_W^{\text{stat}} = 0.6 \text{ MeV}$
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**
    - $BR(W \to e\nu)$ 10.65 ± 0.17
    - $BR(W \to \mu\nu)$ 10.59 ± 0.15
    - $BR(W \to \tau\nu)$ 11.44 ± 0.22
    - $BR(W \to l\nu)$ 10.84 ± 0.09
    - $BR(W \to \text{hadrons})$ 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 $\rightarrow$ Vcs Vcb...

- **Triple Gauge Couplings**
  - Selected LEP limits (95% C.L.)
    - $\Delta k_\gamma$ $[-9.9,6.6] \times 10^{-2}$
    - $\lambda_\gamma$ $[-5.9,1.7] \times 10^{-2}$
    - $\Delta k_Z$ $[-7.4,5.1] \times 10^{-2}$
    - $\lambda_Z$ $[-5.9,1.7] \times 10^{-2}$
    - $\Delta g_1^Z$ $[-5.4,2.1] \times 10^{-2}$

  - FCC-ee: overall improvements by a factor of **50** to compare with LEP

- **The strong coupling constant:**
  - FCC-ee: $\Delta_{r\alpha_S}(m_W^2) = 3 \times 10^{-3}$
    - from hadronic W decays ($\Gamma_W$ and $BR_{W,\text{had}}$)
  - LEP2 precision: 37%
The FCC-ee offers unprecedented precision of electroweak studies!

The expectations of precision for electroweak observables in the sector of $Z$ pole and $WW$ threshold have been discussed:

- $\Delta M_Z = 100$ keV
- $\Delta \Gamma_Z = 100$ keV
- $\Delta M_W = 1$ MeV
- $\Delta \Gamma_W = 1.5$ MeV
- $\Delta_{\text{stat}} \sin^2 \Theta_{W,\text{eff}} = 10^{-7}$

Expectations for coupling constants:

- $\Delta_{\text{rel}} \alpha_{\text{QED}}(m_Z^2) = 3 \times 10^{-5}$
- $\Delta_{\text{rel}} \alpha_S(m_Z^2) = 2 \times 10^{-3}$
- $\Delta_{\text{rel}} \alpha_S(m_W^2) = 3 \times 10^{-3}$

The precision electroweak measurements have very strong sensitivity for New Physics searches.

The other talks about FCC-ee physics:
- Physics at the FCC: a story of synergy and complementarity
- Right-Handed neutrino searches at the FCC
- Higgs measurements at the Future Circular Colliders
- Top-quark physics at the Future Circular Colliders
- QCD and gamma-gamma Physics at FCC-ee
- Flavour Physics at FCC-ee (poster)