EW precision tests at the FCC-ee

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On behalf of
the FCC-ee study group
The FCC: a long-term strategy for HEP

FCC-ee (100 km, $e^+e^-$, 90-400 GeV)
New physics discovery up to 100 TeV via its quantum effects
rare processes very weak couplings (light new physics)”

FCC-hh
$(pp, 100$ TeV$)$
& $e^\pm$ (120 GeV)$-p$ (7, 16 & 50 TeV) collisions FCC-eh

$\geq 60$ years of $e^+e^-$, $pp$, $ep/A$ physics at highest energies
CERN Circular Colliders and FCC

- 1980: Constr.
- 1985: Physics
- 1990: LEP

- 1995: Design
- 2000: Proto
- 2005: Construction
- 2010: Physics
- 2015: LHC

- 2020: Design
- 2025: Construction
- 2030: Physics
- 2035: HL-LHC

- FCC: Design
- Proto
- Construction
- Physics

20 years

(FCC-ee)
FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)

- 2 main IPs in A, G for both machines
- asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector

Common layouts for hh & ee

Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.
# lepton collider parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-ee</th>
<th>LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>physics working point</strong></td>
<td>Z</td>
<td>WW</td>
</tr>
<tr>
<td><strong>energy/beam [GeV]</strong></td>
<td>45.6</td>
<td>80</td>
</tr>
<tr>
<td>bunches/beam</td>
<td>30180</td>
<td>91500</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>7.5</td>
<td>2.5</td>
</tr>
<tr>
<td>bunch population ([10^{11}])</td>
<td>1.0</td>
<td>0.33</td>
</tr>
<tr>
<td><strong>beam current [mA]</strong></td>
<td>1450</td>
<td>1450</td>
</tr>
<tr>
<td><strong>luminosity/IP (x 10^{34}\text{cm}^{-2}\text{s}^{-1})</strong></td>
<td>210</td>
<td>90</td>
</tr>
<tr>
<td><strong>energy loss/turn [GeV]</strong></td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>synchrotron power [MW]</strong></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td><strong>RF voltage [GV]</strong></td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>rms cm (E) spread SR [%]</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>rms cm (E) spread SR+BS [%]</td>
<td>0.15</td>
<td>0.06</td>
</tr>
</tbody>
</table>
• “baseline” is based on a conservative optics with 2 IpS
  all efforts are developed to reach the target
  • overlap linear and circular machines
  Circ: High luminosity, experimental environment (2 to 4 IP), $E_{CM}$ calibration
  Linear: higher energy reach, longitudinal beam polarization
• Z and W Electroweak physics (5x10^{12}Z, 10^8 WW)
  precision energy calibration (100 KeV) \rightarrow m_Z, \Gamma_Z, m_W, \sin^2 \theta_W^{\text{eff}}
  possibly precision measurement of \alpha_{\text{QED}}(m_Z), \alpha_S(m_Z)
  high luminosity search for rare Z decays
  neutrino counting and search for RH neutrinos

• Tera Z is also a Flavour Factory (boosted and tagged b, c, \tau)

• Higgs Physics at \text{E}_{\text{CM}} = 240 \text{ GeV} (ZH) and 350 \text{ GeV}, 2 \times 10^6 ZH events
  unique determination of ZH coupling and H width,
  all fermion and boson couplings (except HHH)
  rare decays

• top quark physics at 350 -370 GeV (ses talk by Freya Blekman)
  top quark mass (essential for precision EW tests) to exp. precision of 10 MeV
  top quark couplings (no need for beam polarization)

• investigating run at \text{E}_{\text{CM}} = m_H to determine Hee coupling

8/6/2016
FCC-ee physics: High-precision W, Z, top

Z resonance: TeraZ

WW threshold scan: OkuW

tt threshold scan: MegaTops

- Lineshape
  - Exquisite $E_{\text{beam}}$ (unique!)
  - $m_Z, \Gamma_Z$ to < 100 keV (2.2 MeV)

- Asymmetries
  - $\sin^2\theta_W$ to $6 \times 10^{-6}$ (1.6 $\times 10^{-4}$)
  - $\alpha_{\text{QED}}(m_Z)$ to $3 \times 10^{-5}$ (1.5 $\times 10^{-4}$)

- Branching ratios, $R_\ell, R_b$
  - $\alpha_s(m_Z)$ to 0.0002 (0.002)

- Threshold scan
  - $m_W$ to 500 keV (15 MeV)
  - Branching ratios $R_\ell, R_{\text{had}}$
    - $\alpha_s(m_W)$ to 0.0002
  - Radiative returns $e^+e^-\gamma Z$
    - $N_\nu$ to 0.0004 (0.008)

- Threshold scan
  - $m_{\text{top}}$ to 10 MeV (500 MeV)
  - $\lambda_{\text{top}}$ to 13%
  - EW couplings to 1%

- Mostly thanks to: (i) huge stats, (ii) threshold scans with $E_{\text{beam}}$ ~ 0.1 MeV

8/6/2016
Beam polarization and E-calibration @ FCC-ee

Precise measurement of $E_{\text{beam}}$ by resonant depolarization

$\sim 100$ keV each time the measurement is made \( \xrightarrow{\text{LEP}} \)

At LEP transverse polarization was achieved routinely at $Z$ peak.

instrumental in $10^{-3}$ measurement of the $Z$ width in 1993

led to prediction of top quark mass (179+ 20 GeV) in Mar’94

At LEP beam energy spread destroyed polarization above 61 GeV

$\sigma_E \propto E^2/\sqrt{\rho}$ \( \xrightarrow{\text{At TLEP}} \) transverse polarization up to at least 81 GeV (WW threshold)

to go to higher energies requires spin rotators and siberian snake

FCC-ee: use ‘single’ bunches to measure the beam energy continuously

\( \xrightarrow{\text{no interpolation errors due to tides, ground motion or trains etc...}} \)

\(<\sim 100\) keV beam energy calibration around $Z$ peak and $W$ pair threshold.

$\Delta m_Z \sim 0.1$ MeV, $\Delta \Gamma_Z \sim 0.1$ MeV, $\Delta m_W \sim 0.5$ MeV
### A Sample of Essential Quantities:

<table>
<thead>
<tr>
<th>$\chi$</th>
<th>Physics</th>
<th>Present precision</th>
<th>TLEP stat Syst Precision</th>
<th>TLEP key</th>
<th>Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_Z$ MeV/c²</td>
<td>Input</td>
<td>$91187.5 \pm 2.1$</td>
<td>$0.005 \text{ MeV} &lt; \pm 0.1 \text{ MeV}$</td>
<td>E_cal</td>
<td>QED corrections</td>
</tr>
<tr>
<td>$\Gamma_Z$ MeV/c²</td>
<td>$\Delta \rho (T)$ (no $\Delta \alpha$!)</td>
<td>$2495.2 \pm 2.3$</td>
<td>$0.008 \text{ MeV} &lt; \pm 0.1 \text{ MeV}$</td>
<td>E_cal</td>
<td>QED corrections</td>
</tr>
<tr>
<td>$R_\ell$</td>
<td>$\alpha_s, \delta_b$</td>
<td>$20.767 \pm 0.025$</td>
<td>$0.0001 \pm 0.002 - 0.0002$</td>
<td>Statistics</td>
<td>QED corrections</td>
</tr>
<tr>
<td>$N_v$</td>
<td>Unitarity of PMNS, sterile $\nu$'s</td>
<td>$2.984 \pm 0.008$</td>
<td>$0.000008 \pm 0.0004$</td>
<td>Statistics</td>
<td>QED corrections to Bhabha scat.</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$\delta_b$</td>
<td>$0.21629 \pm 0.00066$</td>
<td>$0.000003 \pm 0.000020 - 60$</td>
<td>Statistics, small IP</td>
<td>Hemisphere correlations</td>
</tr>
<tr>
<td>$M_W$ MeV/c²</td>
<td>$\Delta \rho, \varepsilon_3, \varepsilon_2, \Delta \alpha (T, S, U)$</td>
<td>$80385 \pm 15$</td>
<td>$0.3 \text{ MeV} &lt; 1 \text{ MeV}$</td>
<td>E_cal &amp; Statistics</td>
<td>QED corrections</td>
</tr>
<tr>
<td>$m_{\text{top}}$ MeV/c²</td>
<td>Input</td>
<td>$173200 \pm 900$</td>
<td>$10 \text{ MeV}$</td>
<td>E_cal &amp; Statistics</td>
<td>Theory limit at 100 MeV?</td>
</tr>
</tbody>
</table>
Uncertainties in $m_{\text{top}}$, $\Delta \alpha(m_z)$, $m_H$, etc....

$\Delta \sin^2 \theta_{\text{lept}}^W \sim \Delta \alpha(m_z)/3 = 10^{-5}$ have to reduce $\Delta \alpha(m_z)$

**New idea:** exploit large statistics of FCC-ee to measure $\alpha_{\text{QED}}(m_z)$ directly close to $m_z$

- Extrapolation error becomes negligible!

Use different sensitivity vs $\sqrt{s}$

nice Z lineshape scan

measure both within the same environment

@ $M_Z$

$A_{\text{FB}}$ to extract $\sin^2 \theta_{\text{lept}}^W$

@ $M_Z + 3$ GeV $M_Z - 3$ GeV to extract $\alpha_{\text{QED}}(M_Z)$

**P. Janot: FCC-ee Physics Vidyo Meeting, June 29th 2015**
Precise determination of $\alpha_{QED}$ form $A_{FB}$

$A_{FB}^{\mu\mu}$ at $\sqrt{s}=87.9$ GeV $\sqrt{s^+}=94.3$ GeV

error cancellation of +3 vs -3 points.

Angular resolution

Beam energy spread

- Total bias on $\alpha_{QED}(m_\mu^2)$ of the order of $8 \times 10^{-5}$
Theoretical limitations

SM predictions (using other input)

\[ M_W = 80.3593 \pm 0.0002 \pm 0.0001 \pm 0.0001 \pm 0.0003 \]

\[ \sin^2 \theta_{\text{eff}}^\ell = 0.231496 \pm 0.0000015 \pm 0.000001 \pm 0.0000001 \pm 0.000001 \pm 0.00001 \]

Experimental errors at FCC-ee will be 20-100 times smaller than the present errors. BUT can be typically 10-30 times smaller than present level of theory errors. Will require significant theoretical effort and additional measurements!

Radiative correction workshop 13-14 July 2015 stressed the need for 3 loop calculations for the future!
in other words .... $\Delta(\Delta \rho) = \pm 10^{-5}$  + several tests of same precision

NB width of this line : Z mass error. Without FCC-ee its 2.2 MeV!
**New physics reach**

**Effective lagrangian Dim-6 operators**

\[
\frac{1}{2} \left( \frac{\bar{c}_W + \bar{c}_B}{m_W^2} (\mathcal{O}_W + \mathcal{O}_B) + \frac{\bar{c}_T}{v^2} \mathcal{O}_T \right) + \frac{\bar{c}_{3L}^l}{v^2} \mathcal{O}_{LL}^{(3)_l} + \frac{\bar{c}_R^l}{v^2} \mathcal{O}_R^l,
\]

\[
\frac{1}{2} \left( \frac{\bar{c}_W - \bar{c}_B}{m_W^2} (\mathcal{O}_W - \mathcal{O}_B) + \frac{\bar{c}_{HW}}{m_W^2} \mathcal{O}_{HW} + \frac{\bar{c}_{HB}}{m_W^2} \mathcal{O}_{HB} + \frac{\bar{c}_g}{m_W^2} \mathcal{O}_g + \frac{\bar{c}_\gamma}{m_W^2} \mathcal{O}_\gamma \right)
\]

\[
+ \frac{\bar{c}_H}{v^2} \mathcal{O}_H + \frac{\bar{c}_f}{v^2} \mathcal{O}_f.
\]

\[
\bar{c}_i = c_i \frac{M^2}{\Lambda^2},
\]

**Model examples:**

MSSM, heavy gauge singlet that couples to the SM via a Higgs portal

**Ellis, You**

1510.04561

**Henning et al**

1404.1058

**Marginalised**

ILC250

FCC-ee

**Sensitive to heavy new physics up to 100 TeV**
Conclusion

lesson from past experience:

Precision EW tests allowed to predict mass of particles before discovery (Top, Higgs) and excluded new physics up to (100 GeV)

FCC-ee will allow sensitivity to new physics up to 100 TeV
Through its effect in quantum corrections

FCC-ee offers a broad, coherent program of EW precision measts on ‘all fronts’.

Transverse polarization is critical for Z and W masses, Z width. (unique feature of circular colliders)

No physics case could be found for longitudinal polarization or Ecm larger than 370 GeV at the FCC-ee: AFB @ large luminosities over-compensate, and the FCC-hh is better suited for higher energy
Resonant depolarization accuracy at TLEP/FCCee – extrapolation

Statistical errors are divided by sqrt(10,000) - negligible
This is a zeroth order working hypothesis
The table should eventually also include effects that were negligible at the time of LEP

<table>
<thead>
<tr>
<th>Source</th>
<th>Correlated/Z mass</th>
<th>Uncorrelated / Z width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron mass</td>
<td>15 keV</td>
<td>0 keV</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>0 keV</td>
<td>0 keV</td>
</tr>
<tr>
<td>Frequency of the RF magnet</td>
<td>1 keV</td>
<td>0 keV</td>
</tr>
<tr>
<td>Width of excited resonance</td>
<td>9 keV</td>
<td>0 keV</td>
</tr>
<tr>
<td>Interference of resonances</td>
<td>9 keV</td>
<td>0 keV</td>
</tr>
<tr>
<td>Spin tune shifts from long. fields</td>
<td>5 keV</td>
<td>0 keV</td>
</tr>
<tr>
<td>Spin tune shifts from hor. fields</td>
<td>100 keV</td>
<td>0 keV</td>
</tr>
<tr>
<td>Quadratic non-linearities</td>
<td>~20 keV</td>
<td>~12 keV</td>
</tr>
<tr>
<td>Total error</td>
<td>~40 keV</td>
<td>~20 keV</td>
</tr>
<tr>
<td></td>
<td>~45 keV</td>
<td>~23 keV</td>
</tr>
</tbody>
</table>

Per beam, not ECM
Extracting physics from $\sin^2 \theta^\text{lept}_W$

1. Direct comparison with $m_Z$

\[
\sin^2 \theta^\text{lept}_W \cos^2 \theta^\text{lept}_W = \left( \frac{\pi \alpha (M^2_Z)}{\sqrt{2} \, G_F \, m^2_Z} \right) \frac{1}{1 + \Delta \rho} \frac{1}{1 - \frac{E^3_\beta}{\tan^2 \theta^\text{lept}_W}}
\]

Uncertainties in $m_{\text{top}}, \Delta \alpha (m_z), m_H,$ etc...

$\Delta \sin^2 \theta^\text{lept}_W \sim \Delta \alpha (m_z)/3 = 10^{-5}$ if we can reduce $\Delta \alpha (m_z)$ (see P. Janot idea)

2. Comparison with $m_w/m_Z$

Compare above formula with similar one:

\[
\sin^2 \theta^\text{lept}_W \cos^2 \theta^\text{lept}_W = \left( \frac{\pi \alpha (M^2_Z)}{\sqrt{2} \, G_F \, m^2_Z} \right) \cdot - \frac{\Delta \rho}{\sin^2 \theta^\text{lept}_W} + \frac{2 \, \sin^2 \theta^\text{lept}_W \, \varepsilon_3 + \frac{c^2 - s^2}{s^2} \, \varepsilon_2}{\sin^2 \theta^\text{lept}_W}
\]

Where it can be seen that $\Delta \alpha (m_z)$ cancels in the relation.

The limiting error is the error on $m_w$.

For $\Delta m_w = 0.5 \text{ MeV}$ this corresponds to $\Delta \sin^2 \theta^\text{lept}_W = 10^{-5}$
## The main players

### Inputs:
- $G_F = 1.1663787(6) \times 10^{-5} \text{ /GeV}^2$
  - from muon life time: $6 \times 10^{-7}$
- $M_Z = 91.1876 \pm 0.0021 \text{ GeV}$
  - Z line shape: $2 \times 10^{-5}$
- $\alpha = 1/137.035999074(44)$
  - electron g-2: $3 \times 10^{-10}$

### EW observables sensitive to new physics:
- $M_W = 80.385 \pm 0.015$
  - LEP, Tevatron: $2 \times 10^{-4}$
- $\sin^2 \theta_W^{\text{eff}} = 0.23153 \pm 0.00016$
  - WA Z pole asymmetries: $7 \times 10^{-4}$
  - $\Gamma_{Rb}$ etc...

### Nuisance parameters:
- $\alpha(M_Z) = 1/127.944(14)$
  - hadronic corrections to running alpha: $1.1 \times 10^{-4}$
- $\alpha_s(M_Z) = 0.1187(17)$
  - strong coupling constant: $1.7 \times 10^{-3}$
- $m_{\text{top}} = 173.34 \pm 0.76 \text{ GeV}$
  - from LHC+Tevatron combination: $4 \times 10^{-3}$
- $m_H = 125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.) GeV/c}^2$ (CMS+ATLAS): $2 \times 10^{-3}$
relations to the well measured $G_F, m_Z, \alpha_{\text{QED}}$

at first order:

$$
\Delta \rho = \frac{\alpha}{\pi} \left( \frac{m_{\text{top}}}{m_Z} \right)^2
- \frac{\alpha}{4\pi} \log \left( \frac{m_h}{m_Z} \right)^2
$$

$$
\varepsilon_3 = \cos^2 \theta_w \frac{\alpha}{9\pi} \log \left( \frac{m_h}{m_Z} \right)^2
$$

$$
\delta_{vb} = \frac{20}{13} \frac{\alpha}{\pi} \left( \frac{m_{\text{top}}}{m_Z} \right)^2
$$

complete formulae at 2d order including strong corrections are available in fitting codes e.g. ZFITTER, GFITTER

$\sin^2 \theta_w^{\text{eff}}$ is defined from

$$
\sin^2 \theta_w^{\text{eff}} = \frac{1}{4} \left( 1 - \frac{g_{\nu e}}{g_{\nu e}^{\text{opt}}} \right) = \sin^2 \theta_w + \varepsilon_2
$$

obtained from asymmetries at the $Z$. 

also

$$
m_W^2 = \frac{\pi d \alpha (m_Z^2)}{\sqrt{2} G_F \sin^2 \theta_w^{\text{eff}}} \cdot \frac{1}{\left( 1 - \varepsilon_3 + \varepsilon_2 \right)}
$$

$$
\Delta \alpha = \Delta \alpha = \frac{\cos^2 \theta_w}{\sin^2 \theta_w} \Delta \rho + 2 \frac{\cos^2 \theta_w}{\sin^2 \theta_w} \varepsilon_3 + \frac{\cos^2 \theta_w}{\sin^2 \theta_w} \varepsilon_2
$$
Experimental conditions

- 2-4 IPs $L^* \sim 2\text{m}$
- bunch crossing spacing from 2-5 ns (Z) up to 3$\mu$s (top)
- no pile-up (<0.001 at FCC-Z/CrabWaist)
- beamstrahlung is mild for experiments

**Experimental conditions**

<table>
<thead>
<tr>
<th></th>
<th>FCCZ</th>
<th>FCCZ, c.w</th>
<th>CEPC</th>
<th>FCC ZH</th>
<th>ILC500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Npairs / BX</td>
<td>200</td>
<td>9900</td>
<td>3260</td>
<td>640</td>
<td>165000</td>
</tr>
<tr>
<td>Leading process</td>
<td>96% LL</td>
<td>65% LL</td>
<td>80% LL</td>
<td>90% LL</td>
<td>60% BH</td>
</tr>
<tr>
<td>Epairs / BX (GeV)</td>
<td>86</td>
<td>2940</td>
<td>2600</td>
<td>570</td>
<td>400000</td>
</tr>
<tr>
<td>Leading process</td>
<td>100% LL</td>
<td>100% LL</td>
<td>98% LL</td>
<td>96% LL</td>
<td>70% BH</td>
</tr>
</tbody>
</table>

- Beam energy calibration for Z and W running
- IR design with crossing angle is not trivial

⇒ a challenging magnet design issue.
Input from Physics to the accelerator design

0. Nobody complains that the luminosity is too high (the more you get, the more you want)
no pile up, even at the Z: at most 1ev /300bx

1. Do we need polarized beams?
   -1- transverse polarization:
     continuous beam Energy calibration with resonant depolarization
     central to the precision measurements of \( m_z, m_w, \Gamma_z \)
     requires ‘single bunches’ and calibration of both e+ and e-
     a priori doable up to W energies -- workarounds exist above (e.g. \( \gamma Z \) events)
     large ring with small emittance excellent. Saw-tooth smaller than LEP for Z
     need wigglers (or else inject polarized e- and e+) to polarize ‘singles’;
     simulations ongoing (E. Gianfelice, M. Koratzinos, I.Kopp)

   -2- longitudinal polarization requires spin rotators and is very difficult at high energies
     -- We recently found that it is not necessary to extract top couplings (Janot)
     -- improves Z peak measurements if loss in luminosity is not too strong
       but brings no information that is not otherwise accessible

2. What energies are necessary?
   -- in addition to Z, W, H and top listed the following are being considered
     -- e+e- \( \rightarrow \) H(125.2) (requires monochromatization A. Faus) (under study)
     -- e+e- at top threshold + ~20 GeV for top couplings (\( E_{\text{max}} \) up to 180 -185 GeV)
     -- no obvious case for going to 500 GeV