Precision measurements at FCC-ee
requirements on theor and experiments
Motivation (well known)

for the precision measurements and associated precision calculations

1. given that the SM is complete with the Higgs discovery, how do we find out:
   -- if the Higgs boson is exactly what is foreseen by the standard model, shifting the energy levels of the whole universe to generate particle masses?
   -- where/what are the new physics phenomena that must be present to explain:
     baryon asymmetry
     dark matter,
     neutrino masses (and other mysteries we don’t understand)

2. one of the most powerful and broadly efficient methods is to perform precision measurements at a level that will establish the Higgs boson properties and could be sensitive to new physics:
   -- this requires identification of the observables that contain sensitivity to new phenomena, either by loops, direct long distance propagator effects, or mixing with known particles.
   -- then requires high precision theory both to extract these observables in a precise way from experiment, and high precision calculations to compare with the theory
   -- this also requires precise measurements of ancillary quantities (alpha_QED, gHZZ or TTZ couplings) that will be used for other precise measurements
   -- and require themselves high precision theory to be extracted from experiment.
Theory and experiment communicate by way of observables

or pseudo-observables that are extracted from experimental measurements using well defined and minimally model-dependent prescriptions.

This was possible at LEP Z and W for such things as QED corrected line-shape parameters and cross-sections, \( \Rightarrow \) mass, width, peak cross-section, partial widths or branching ratios, polarization or forward-backward cross-section asymmetries

model dependence was that
1) QED is correct;
2) weak interaction is V,A (or L,R)
3) final states are e mu tau, invisible, hadrons (including b, c)
4) other possible final states had been searched exclusively

This was well adapted to the problems of the day:
-- what are the masses of top and Higgs
-- is there evidence of new physics in loops? In particular: is there breaking of SU(2) custodial symmetry \( (\rho_0 \neq 1) \) ?
One very common source of confusion is the **definition of the weak mixing angle**

-- for the sake of calculations it is often practical for theorists to define (rather, note) 

\[ \sin^2 \theta_W = 1 - \frac{m_W^2}{m_Z^2} \] 

**experimenters**: at high energy this is a completely useless quantity, redundant with the measurements of masses of W and Z. **FORGET THIS, PLEASE.**

The SM lagrangian also introduces the electric charge \( e \) and the weak coupling \( g \), and 

\[ \sin \theta_W = \frac{e}{g} \]

this is never measured as such, but the following closely related quantity is obtained from the **chiral couplings** 

\[ g_{R,L} = I^3 - Q \sin^2 \theta_W^{\text{eff}} \]

for electron: \( g_{Re} = - e \sin^2 \theta_W \), \( g_{Le} = - \frac{1}{2} - e \sin^2 \theta_W \)

observables will be all Z pole asymmetries

\[ A_{LR} = \mathcal{P} A_e, \quad \text{and} \quad A_{FB,\text{pol}}^f = \frac{3}{4} \mathcal{P} A_f. \]

\[ A_{FB}^f = \frac{3}{4} A_e A_f, \quad \langle P_\tau \rangle = - A_\tau, \quad \text{and} \quad A_{FB,\text{pol}}^f = \frac{3}{4} A_e. \]

\[ \uparrow \text{with beam polarization } P \]

or without
Thus at LEP we defined $\sin^2\theta_W^{\text{eff}}$ as the short hand notation for the electron chiral coupling asymmetry or $\sin^2\theta_W^{\text{eff}} = \frac{1}{4}(1-g_{Ve}/g_{Ae})$

$$A_{FB}^f = \frac{3}{4} A_e A_f, \quad \langle P_\tau \rangle = -A_\tau, \quad \text{and} \quad A_{FB,\text{pol}}^f = \frac{3}{4} A_e.$$ 

NB this enters in all $A_{FB}$s (leptons, b,c,qs) as driving term in heavy physics sensitivity because the Z is initially polarized due to the electron coupling asymmetry.
Theoretical tasks

1. identify observables that contain sensitivity to new phenomena, either by loops → Universal (in photon, Z, W propagators) → S,T,U loops → flavour dependent (in boxes and vertices) → $\delta_b$
direct long distance propagator effects, (ex: new Z’) flavour, or quark lepton univ. violation mixing with known particles (Z’-Z mixing , $\nu$-N mixing)
   neutrino and flavour dependent violations,

2. high precision SM theory to extract these observables in a precise way from experiment
   (precise QED, QCD Monte-Carlo or ISR radiator )

3. high precision calculations of observables in SM to compare with experiment
   precise multi-loop SM calculation starting from $m_Z, G_F, \alpha_{\text{QED}} (m_Z), \alpha_{\text{QCD}} (m_Z), m_H, m_t \{m_f\}$
   -- this also requires precise measurements of ancillary quantities (alpha_QED, mt, etc) that will be used for other precise measurements
   -- and require themselves high precision theory to be extracted from experiment.
pleased please produce this in 2038 for as man observables as possible
(Sensiitiities earlier to optimize run plan)

direction of sensitivity for parameter P

direction of sensitivity for NP A

 SM prediction at $10^{-5}$ level
(keep secret?)

direction of sensitivity for NP B

direction of sensitivity for symmetry violation V

2040 result
The most solid inputs to this discussion are
-- statistics
-- time scale
see next slides.

In practice we can give with some confidence the statistical uncertainties, both for experimental observables and ancillary parameters.

In the CDR we give a set of 'estimates' for systematics which are (not totally consistently)
-- either 'we are sure we an do better than that'
-- or 'we think it will take some work to go beyond this level and we don't know where we will arrive'.

➔ our goal is to reduce both experimental and theory systematics as far as possible.
➔ 'statistics is the limit'
Event statistics:

- **Z peak**
  - $E_{cm} : 91$ GeV
  - $5 \times 10^{12}$ e+e- → Z

- **WW threshold**
  - $E_{cm} : 161$ GeV
  - $10^8$ e+e- → WW

- **ZH threshold**
  - $E_{cm} : 240$ GeV
  - $10^6$ e+e- → ZH

- **tt threshold**
  - $E_{cm} : 350$ GeV
  - $10^6$ e+e- → tt

- **LEP x 2.10^5**
  - Never done
  - 2 MeV

- **LEP x 2.10^3**
  - Never done
  - 5 MeV

the LEP statistics of $1.6 \times 10^7$ hadronized Z’s will be produced in 200 seconds at FCC-ee(Z)
Great energy range for the heavy particles of the Standard Model

COMPLEMENTARITY WITH LINEAR COLLIDERS (ILC, CLIC) overlap 300-400 GeV
certainly could imagine a world with 1 circular lab and 1 linear lab!
FCC-ee run plan

Table 2.1: Run plan for FCC-ee in its baseline configuration with two experiments. The number of $WW$ events is given for the entirety of the FCC-ee running at and above the $WW$ threshold.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Run duration (years)</th>
<th>Center-of-mass Energies (GeV)</th>
<th>Integrated Luminosity (ab$^{-1}$)</th>
<th>Event Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC-ee-Z</td>
<td>4</td>
<td>88-95</td>
<td>150</td>
<td>$3 \times 10^{12}$ visible $Z$ decays</td>
</tr>
<tr>
<td>FCC-ee-W</td>
<td>2</td>
<td>158-162</td>
<td>12</td>
<td>$10^8$ WW events</td>
</tr>
<tr>
<td>FCC-ee-H</td>
<td>3</td>
<td>240</td>
<td>5</td>
<td>$10^6$ $ZH$ events</td>
</tr>
<tr>
<td>FCC-ee-tt</td>
<td>5</td>
<td>345-365</td>
<td>1.5</td>
<td>$10^6$ $t\bar{t}$ events</td>
</tr>
</tbody>
</table>

1. Obviously this is a working assumption; order of $Z,W$ and $H$ points can be changed, this will all be decided close to turn on.

2. $e^+e^- \rightarrow H$ ($ECM = m_H$) unique, not in the schedule so far.

3. Transverse polarization $\rightarrow$ precision beam energy. Longitudinal possible (for both beams) but not in CDR by choice.
FCC integrated project timeline

1. Project preparation & administrative processes
2. Project preparation & administrative processes
3. Funding strategy
4. Geological investigations, infrastructure detailed design and tendering preparation
5. Tunnel, site and technical infrastructure construction
6. Superconducting wire and magnet R&D
7. FCC-ee accelerator R&D and technical design
8. FCC-ee detector construction, installation, commissioning
9. Set up of international experiment collaborations, detector R&D and concept development
10. FCC-ee detector technical design
11. FCC-ee detector construction, installation, commissioning
12. Fundings
13. Permissions
14. Update Permissions
15. Fundings and in-kind contribution agreements
16. FCC-ee dismantling, CE & infrastructure adaptations FCC-hh
17. SC wire and 16 T magnet R&D, model magnets, prototypes, preseries
18. 16 T dipole magnet series production
19. FCC-ee accelerator construction, installation, commissioning
20. FCC-ee accelerator R&D and technical design
21. FCC-hh accelerator R&D and technical design
22. FCC-hh accelerator construction, installation, commissioning
23. FCC-hh detector R&D, technical design
24. FCC-hh detector construction, installation, commissioning
25. FCC-ee 15 yrs operation
26. FCC-hh ~ 25 years
27. FCC-ee detector construction, installation, commissioning
28. FCC-ee detector technical design
29. FCC-ee accelerator R&D and technical design
30. FCC-ee accelerator construction, installation, commissioning
31. FCC-ee detector construction, installation, commissioning
32. FCC-hh detector construction, installation, commissioning
33. FCC-hh detector technical design
34. FCC-ee 15 yrs operation
35. FCC-ee 15 yrs operation
36. FCC-ee 15 yrs operation
37. FCC-ee 15 yrs operation
38. FCC-ee 15 yrs operation
39. FCC-ee 15 yrs operation
40. FCC-ee 15 yrs operation
41. FCC-ee 15 yrs operation
42. FCC-ee 15 yrs operation
43. FCC-ee 15 yrs operation
44. FCC-ee 15 yrs operation
45. FCC-ee 15 yrs operation
46. FCC-ee 15 yrs operation
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66. FCC-ee 15 yrs operation
67. FCC-ee 15 yrs operation
68. FCC-ee 15 yrs operation
69. FCC-ee 15 yrs operation
70. FCC-ee 15 yrs operation

70 years seems like a long time!

work is cut out for physics and detectors
Examples
Precision EW measurements: is the SM complete?

-^- EFT D6 operators (some assumptions)
-^- Higgs and EWPOs are complementary
-^- top quark mass and couplings essential!
  (the 100km circumference is optimal for this)

<-- many systematics are preliminary and should improve with more work.
<-- tau b and c observables still to be added
<-- complemented by high energy FCC-hh

Theory work is critical and initiated
status as of briefing book
still based on (conservative)
experimental and theory errors:

our goal: work out systematics until we reach statistical level:

(a lot of work to do!)
**FCC-ee**  
-- EWPO: sensitivity $10^{-5}$ up to very high masses  
-- high sensitivity to single $N(\rightarrow l_2^\pm W)$ in Z decay  

**FCC-hh**  
-- production in $W\rightarrow l_1^\pm + N(\rightarrow l_2^\pm W)$ (LNV+LFV) with initial and final lepton charge and flavour  

**FCC e-p**  
-- production in CC $e^\pm p \rightarrow X N(\rightarrow l^\pm W)$ high mass  

**Complementarity:** discovery + studies of FNV and LFV!

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Massive neutrino mechanisms for generating the matter-antimatter asymmetry in the Universe should be a central consideration in the selection and design of future colliders. *(neutrino town meeting report to ESPP)*
The relationship \(|U|^2 \propto \theta^2 \approx m_\nu / m_N\) is valid for one family see-saw. For two or three families the mixing can be larger (Shaposhnikov) Antush and Fisher have shown that a slight # in Majorana mass can generate larger mixing between the left- and right-handed neutrinos. **Worth exploring.**

\[\nu_L = \nu \cos \theta + N \sin \theta \rightarrow (\cos \theta)^2\]

becomes parametrized as \(1 + \varepsilon_{\alpha\beta} (\varepsilon_{\alpha\alpha} \text{ is negative})\) the coupling to light neutrinos is typically suppressed. In the \(G_F, M_Z, \alpha_{QED}\) scheme, \(G_F\) (extracted from \(\mu \rightarrow e\nu_e \nu_\mu\)) and \(g\) should be increased. This leads to *correlated* variations of all predictions upon e or mu neutrino mixing. Only the ‘number of neutrinos’ \(R_{\text{inv}}^\text{e} \text{ and } \sigma_{\text{had}}^\text{peak}\) is sensitive to the tau-neutrino mixing.

<table>
<thead>
<tr>
<th>Prediction in MUV</th>
<th>Prediction in the SM</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>([R_\ell]<em>{\text{SM}} (1 - 0.15(\varepsilon</em>{ee} + \varepsilon_{\mu\mu})))</td>
<td>20.744(11)</td>
<td>20.767(25)</td>
</tr>
<tr>
<td>([R_b]<em>{\text{SM}} (1 + 0.03(\varepsilon</em>{ee} + \varepsilon_{\mu\mu})))</td>
<td>0.21577(4)</td>
<td>0.21629(66)</td>
</tr>
<tr>
<td>([R_c]<em>{\text{SM}} (1 - 0.06(\varepsilon</em>{ee} + \varepsilon_{\mu\mu})))</td>
<td>0.17226(6)</td>
<td>0.1721(30)</td>
</tr>
<tr>
<td>([\sigma_{\text{had}}^0]<em>{\text{SM}} (1 - 0.25(\varepsilon</em>{ee} + \varepsilon_{\mu\mu}) - 0.27\varepsilon_\tau))</td>
<td>41.470(15) nb</td>
<td>41.541(37) nb</td>
</tr>
<tr>
<td>([R_{\text{inv}}]<em>{\text{SM}} (1 + 0.75(\varepsilon</em>{ee} + \varepsilon_{\mu\mu}) + 0.67\varepsilon_\tau))</td>
<td>5.9723(10)</td>
<td>5.942(16)</td>
</tr>
<tr>
<td>([M_W]<em>{\text{SM}} (1 - 0.11(\varepsilon</em>{ee} + \varepsilon_{\mu\mu})))</td>
<td>80.359(11) GeV</td>
<td>80.385(15) GeV</td>
</tr>
<tr>
<td>([\Gamma_{\text{lept}}]<em>{\text{SM}} (1 - 0.59(\varepsilon</em>{ee} + \varepsilon_{\mu\mu})))</td>
<td>83.966(12) MeV</td>
<td>83.984(86) MeV</td>
</tr>
<tr>
<td>([[s_{W,\text{eff}}^\text{lep}]^2]<em>{\text{SM}} (1 + 0.71(\varepsilon</em>{ee} + \varepsilon_{\mu\mu})))</td>
<td>0.23150(1)</td>
<td>0.23113(21)</td>
</tr>
<tr>
<td>([[s_{W,\text{eff}}^\text{had}]^2]<em>{\text{SM}} (1 + 0.71(\varepsilon</em>{ee} + \varepsilon_{\mu\mu})))</td>
<td>0.23150(1)</td>
<td>0.23222(27)</td>
</tr>
</tbody>
</table>

Table 1: Experimental results and SM predictions for the EWPO, and the modification in the MUV scheme, to first order in the parameters \(\varepsilon_{\alpha\beta}\). The theoretical predictions and experimental values are taken from Ref. [16]. The values of \((s_{W,\text{eff}}^\text{lep})^2\) and \((s_{W,\text{eff}}^\text{had})^2\) are taken from Ref. [17].
Other quantities that could be sensitive to the light-heavy mixing

1. **the tau life time** would be sensitive to $\varepsilon_{\tau\tau}$
   → how well can we measure the tau life time with $10^{11}\tau\tau$?
   $\tau_\tau = (290.3 \pm 0.5) \times 10^{-15}$ s  \  $c\tau_\tau = 87.03$ $\mu$m
   Mass $m = 1776.86 \pm 0.12$ MeV limits the sensitivity to $0.3 \times 10^{-4}$
   this must be completed by tau leptonic branching ratios

2. the measurement of the ‘number of neutrinos’ at the Z or in radiatie returns
   (see R. Aleksan’s talk on thursday)
From the work presented yesterday by J Wenninger, we estimated the beam energy related errors on the line shape parameters.

\[ m_Z, \Gamma_Z, A_{FB}^\mu \text{ (Pole)} \text{ and } \alpha_{\text{QED}}(m_Z) \text{ from the slope of } A_{FB}(s) \]

These are only the beam energy related errors, must add lumi errors.

One of the ways to reduce the point to point errors is to use the muon momentum distribution.
Polarization effects and left-right coupling asymmetries

This is very old stuff → (see e.g. A. B. Beam Polarization in e+e- annihilation, http://cds.cern.ch/record/252128 , 1993 pp 30-32)

the main points are
-- with beam helicity the quantity $A_{LR}$ can be measured with full statistics of hadrons
-- need both e+ and e- polarization flip to constrain the otherwise limiting error on the beam polarization → $\Delta A_e / A_e = 5 \times 10^{-4}$ for ILC

-- without beam helicity the variation of tau polarization with polar angle allows a determination of the electron coupling asymmetry with $1.7 \times 10^{11}$ tau pairs the $\tau \rightarrow \pi \nu$ and $\rho \nu$ allow $\Delta A_e / A_e = 10^{-4}$ for FCC-ee
This was very well shown by R. Tenchini at the FCC meeting in Amsterdam and at the FCC CDR presentation at CERN [https://indico.cern.ch/event/789349/]

**tau polarization plays a central role at FCC-ee**

- Separate measurements of $A_e$ and $A_\tau$ from

$$P_\tau(\cos \theta) = \frac{A_{pol}(1 + \cos^2 \theta) + \frac{8}{3} A_{pol}^{FB} \cos \theta}{(1 + \cos^2 \theta) + \frac{8}{3} A_{FB} \cos \theta}$$

At FCC-ee
- very high statistics: improved knowledge of tau parameters (e.g. branching fraction, tau decay modeling) with FCC-ee data
- use best decay channels (e.g. $\tau \to \rho \nu_\tau$ decay very clean), note that detector performance for photons / $\pi^0$ very relevant

$\Rightarrow$ measure $\sin^2 \theta_{\text{eff}}$ with $6.6 \times 10^{-6}$ precision

NB this is a relative precision of $\Delta A_e/A_e = 10^{-4}$
(the purely statistical error is about three times smaller)
Precisions on coupling ratio factors, $A_f$

\[ A_e = \frac{2g_V g_{Ae}}{(g_V)^2 + (g_{Ae})^2} = \frac{2g_V / g_{Ae}}{1 + (g_V / g_{Ae})^2} \]

<table>
<thead>
<tr>
<th></th>
<th>Statistical uncertainty</th>
<th>Systematic uncertainty</th>
<th>Improvement w.r.t. LEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_e$</td>
<td>$5. \times 10^{-5}$</td>
<td>$1. \times 10^{-4}$</td>
<td>50</td>
</tr>
<tr>
<td>$A_\mu$</td>
<td>$2.5 \times 10^{-5}$</td>
<td>$1.5 \times 10^{-4}$</td>
<td>30</td>
</tr>
<tr>
<td>$A_T$</td>
<td>$4. \times 10^{-5}$</td>
<td>$3. \times 10^{-4}$</td>
<td>15</td>
</tr>
<tr>
<td>$A_b$</td>
<td>$2 \times 10^{-4}$</td>
<td>$30 \times 10^{-4}$</td>
<td>5</td>
</tr>
<tr>
<td>$A_c$</td>
<td>$3 \times 10^{-4}$</td>
<td>$80 \times 10^{-4}$</td>
<td>4</td>
</tr>
<tr>
<td>$\sin^2 \theta_{W,\text{eff}}$ (from muon FB)</td>
<td>$10^{-7}$</td>
<td>$5. \times 10^{-6}$</td>
<td>100</td>
</tr>
<tr>
<td>$\sin^2 \theta_{W,\text{eff}}$ (from tau pol)</td>
<td>$10^{-7}$</td>
<td>$6.6 \times 10^{-6}$</td>
<td>75</td>
</tr>
</tbody>
</table>
The magic formula appears in the LEP EW paper on the Z pole arXiv:hep-ex/0509008v3

\[ P_\tau(\cos \theta_{\tau^\pm}) = \frac{-A_\tau(1 + \cos^2 \theta_{\tau^\pm}) + 2A_e \cos \theta_{\tau^\pm}}{(1 + \cos^2 \theta_{\tau^\pm}) + \frac{8}{3} A_{FB}^\tau \cos \theta_{\tau^\pm}}. \] (4.2)

The $\tau$ polarisation measurements allow for the determination of $A_\tau$ and $A_e$ and are largely insensitive to $A_{FB}^\tau$.

the most extensive publication is the ALEPH tau polarization paper arXiv:hep-ex/0104038v1 20 Apr 2001
It is evident that a combined analysis of $\tau \rightarrow \pi \nu$ and $\rho \nu$ is essentially limited (for the angular distribution) by the MC statistics and other data-controlable quantities.

Nevertheless, a dedicated simulation and analysis of this essential channel should be foreseen in the next years to evaluate the requirements on detector to achieve this precision. (geometry precision and hermiticity to photons and charged tracks)
NC couplings from Z partial widths

Precisions on normalized partial widths

\[ R_f = \sigma_f / \sigma_{\text{had}} \]

<table>
<thead>
<tr>
<th></th>
<th>Statistical uncertainty</th>
<th>Systematic uncertainty</th>
<th>improvement w.r.t. LEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_\mu ) (( R_\ell ))</td>
<td>10^{-6}</td>
<td>5 \times 10^{-5}</td>
<td>20</td>
</tr>
<tr>
<td>( R_\tau )</td>
<td>1.5 \times 10^{-6}</td>
<td>10^{-4}</td>
<td>20</td>
</tr>
<tr>
<td>( R_e )</td>
<td>1.5 \times 10^{-6}</td>
<td>3 \times 10^{-4}</td>
<td>20</td>
</tr>
<tr>
<td>( R_b )</td>
<td>5 \times 10^{-5}</td>
<td>3 \times 10^{-4}</td>
<td>10</td>
</tr>
<tr>
<td>( R_c )</td>
<td>1.5 \times 10^{-4}</td>
<td>15 \times 10^{-4}</td>
<td>10</td>
</tr>
</tbody>
</table>

We should revisit the relative precisions. Also the measurement of the electron coupling from the peak cross-section for electron pairs (proportional to \( \Gamma_e^2 / \Gamma_Z^2 \)) should be included as it should provide better precision (0.5 \( 10^{-4} \) from lumi measurement at \( 10^{-4} \) precision)

\[ \Rightarrow \] all ratios of partial widths should be known better than \( 10^{-4} \)

\[ \sigma_f^0 = \frac{12\pi (hc)^2 \Gamma_e \Gamma_f}{M_Z^2 \Gamma_Z^2} = \]
Table 5: Comparisons between the ILC GigaZ and FCC-ee TeraZ for the measurements of left-right coupling asymmetries, tests of lepton universality, and measurements of the effective weak mixing angle at the Z pole. Also indicated is the limiting precision on the effective mixing angle from the precision on $\alpha_{\text{QED}}(m_Z^2)$ taking into account for FCC-ee of the improvement on this quantity from the off-peak measurement of the muon forward-backward asymmetry [63].

<table>
<thead>
<tr>
<th>Facility</th>
<th>ILC-GigaZ</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$ produced at the peak</td>
<td>$10^9$</td>
<td>$4 \times 10^{12}$</td>
</tr>
<tr>
<td>Longitudinal polarization $(P_{e^-}, P_{e^-})$</td>
<td>$(\pm 0.8, 0.0)$</td>
<td>$(0.0, 0.0)$</td>
</tr>
<tr>
<td>$\Delta A_e$</td>
<td>$1.2 \times 10^{-4}$</td>
<td>$1.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\Delta A_\mu$</td>
<td>$3 \times 10^{-4}$</td>
<td>$5 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\Delta A_\tau$</td>
<td>$3 \times 10^{-4}$</td>
<td>$5 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\Delta A_\mu/A_e$</td>
<td>$1.6 \times 10^{-3}$</td>
<td>$2.5$ to $4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Delta A_\mu/A_\tau$</td>
<td>$2.3 \times 10^{-3}$</td>
<td>$3.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Delta \sin^2 \theta_W^{\text{eff}}$</td>
<td>$1.5 \times 10^{-5}$</td>
<td>$6 \times 10^{-6}$</td>
</tr>
<tr>
<td>Hard limit on SM prediction: $\Delta \sin^2 \theta_W^{\text{eff}}$ from $\alpha_{\text{QED}}(m_Z^2)$</td>
<td>$1.1 \times 10^{-5}$</td>
<td>$7 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

this table produced for arXiv:1906.02693v1 (FCC-ee your questions asked) will be extended to include the other results that follow.
CC couplings

Present status

The best knowledge of the lepton coupling comes from the measurements of the tau mass / life time and branching ratios

\[
\left( \frac{g_\tau}{g_\mu} \right)^2 = \frac{\tau_\mu}{\tau_\tau} \left( \frac{m_\mu}{m_\tau} \right)^5 B_e \frac{f \left( \frac{m_\tau^2}{m_\mu^2} \right)}{f \left( \frac{m_\tau^2}{m_\tau^2} \right)} \Delta_W \Delta_\gamma, \tag{25}
\]

\[
\left( \frac{g_\tau}{g_e} \right)^2 = \frac{\tau_\mu}{\tau_\tau} \left( \frac{m_\mu}{m_\tau} \right)^5 B_\mu \frac{f \left( \frac{m_\tau^2}{m_\mu^2} \right)}{f \left( \frac{m_\tau^2}{m_\tau^2} \right)} \Delta_W \Delta_\gamma, \tag{26}
\]

where \( f \left( \frac{m_\tau^2}{m_\mu^2} \right) = 0.9998 \), \( \Delta_W = \frac{\delta_W}{\delta_W} = 1 - 2.9 \times 10^{-4} \), \( \Delta_\gamma = \frac{\delta_\gamma}{\delta_\gamma} = 1 + 8.5 \times 10^{-5} \), and \( \tau_\tau \) is the lepton \( \tau \) lifetime.

The present average is still dominated by LEP results and stands at a precision of \( 1.5 \times 10^{-3} \)

\[
\frac{g_\tau}{g_\mu} = 1.0010 \pm 0.0015; \frac{g_\tau}{g_e} = 1.0029 \pm 0.0015
\]

Improvement of the tau lifetime will come at FCC-ee wrt LEP by improved resolution typically proportional to beam pipe radius \( x \) detector resolution. We should already gain a factor nearly 10 intrinsically and 100 in statistics.

The of \( 1.7 \times 10^{11} \) tau pairs should allow to reduce these uncertainties to the \( 10^{-5} \) level
Improve Lepton flavour violation sensitivity by 3 orders of magnitude

\[ \mathcal{B}(Z \rightarrow \tau^{\pm} \ell^{\mp}) < 10^{-9} \text{ @ 95\% C.L.} \]

tau branching ratios are a good test of Universality of the \( \alpha - \nu_\alpha \) CC coupling \( \alpha = e \mu \tau \)

\( \Rightarrow \) sensitive to light-heavy neutrino mixing

(Can someone re-measure the tau mass better?)

and many more....

<table>
<thead>
<tr>
<th>Property</th>
<th>Current WA</th>
<th>FCC-ee stat</th>
<th>FCC-ee syst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass [MeV]</td>
<td>1776.86 +/- 0.12</td>
<td>0.004</td>
<td>0.1</td>
</tr>
<tr>
<td>Electron BF [%]</td>
<td>17.82 +/- 0.05</td>
<td>0.0001</td>
<td>0.003</td>
</tr>
<tr>
<td>Muon BF [%]</td>
<td>17.39 +/- 0.05</td>
<td>0.0001</td>
<td>0.003</td>
</tr>
<tr>
<td>Lifetime [fs]</td>
<td>290.3 +/- 0.5</td>
<td>0.005</td>
<td>0.04</td>
</tr>
</tbody>
</table>

«systematics will be at least this good» probably much better \( \Rightarrow \) to be studied further!

Lepton universality with \( m_\tau = 1776.86 \pm 0.12 \text{ MeV} \)
Lepton Flavour Violating-$\tau$ decays

- Benefits from the huge statistics and boosted topologies.
- Calorimetric performance as ILD.
- Main backgrounds are initial and final state radiative events.

<table>
<thead>
<tr>
<th>Decay</th>
<th>Current bound</th>
<th>FCC-ee sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu \gamma$</td>
<td>$4.4 \times 10^{-8}$</td>
<td>$2 \times 10^{-9}$</td>
</tr>
<tr>
<td>$\tau \rightarrow 3\mu$</td>
<td>$2 \times 10^{-8}$</td>
<td>$10^{-10}$</td>
</tr>
</tbody>
</table>
Beam-induced effects on the luminosity measurement

Precision goal at the Z peak and WW:
- $10^{-4}$ (absolute), a few $10^{-5}$ (relative, line-shape scan)

Focusing of the Bhabha $e^+/-$ by the beam force:

- The # of $e^+/-$ that end up in the acceptance of the LumiCal is reduced: $L$ measured $< L$ true

At the Z peak:
- $< \Delta \theta > \approx 40 \ \mu\text{rad}$

Leads to $\Delta L / L \approx 0.2 \%$
- i.e. 20x larger than the target!

Needs to be corrected for. The precision on the correction factor should be about 5% to ensure a residual systematic below 10-4.
Correction can be calculated in principle... but desirable to determine it experimentally.

Numbers refer to the Z peak.

Bhabha electrons at LEP were also affected by the beam-induced focusing!

Typical focusing was $O$ (10 $\mu$rad)
Leads to a bias on the luminosity of about 0.1 %
- Not accounted for by the experiments
- Large compared to the quoted uncertainties (e.g. OPAL: 0.034% (exp), 0.056% (theo.))

E. Perez

Voutsinas et al, arXiv:1908.01704
No pileup, no underlying event, and demonstrated to be feasible but:

- Extremely large statistics / statistical precision
- ...need small systematics ($10^{-5}$) to match
- Physics event rates up to 100 kHz
- Bunch spacing down to 20 ns
- Continuous beams, no power pulsing
- Complex interaction region
- Beam pipe $\varnothing$ 2-3 cm

Optimization to be done for extremely rich physics capabilities, especially at the Z pole
$10^{12} \ bb, \ cc, \ 2 \ 10^{11} \ \tau\tau, \ etc...$

-- search for rare processes $\rightarrow$ excellent acceptance closure, sensitivity to displaced vertices
-- luminosity measurement at $10^{-5}$ (rel), $10^{-4}$ (abs)
-- acceptance definition at $\leq 10^{-5}$
-- optimal b/c/gluon separation
-- PID (TOF, dE/dx, Ckov?)
-- determination of point-to-point scan energies at 10 keV level

NEW challenges in design, technology, metrology, stability, monitoring
FCC-ee Detector Specificities

In general the physics requirements are similar to those of the LC (ILC/CLIC) detectors. Top energy being smaller the precision on momentum (and strength of magnetic field, depth of calorimeter etc..) can be somewhat relaxed (2T is sufficient).

There are some specific hard challenges at the Z peak run and for extreme precision measurements, as well as for the Flavour physics which is more limited at LC, ATLAS&CMS

1. measurement of the ratio of hadrons to leptons as well as leptonic cross-section.
   \[ R_{\text{lep}} = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \ell^+\ell^-)} \]
   This measurement is sensitive to \(\alpha_{\text{QCD}}\) and the b vertex correction.
   - \(3 \times 10^{12}\) e+e-\(\rightarrow\)Z \(\rightarrow\) Hadron events
   - \(1.5 \times 10^{11}\) e+e-\(\rightarrow\)Z\(\rightarrow\)\(\mu\mu\)\(\tau\tau\)ee each \(\sim 5 \times 10^{11}\) for all leptons.

aim is systematic error < statistical error of \(O(2-3 \times 10^{-6})\)

-- detector acceptance to be defined with precision linked to lepton angular acceptance for an acceptance limit at 15 degrees, this corresponds to an angle known on average with a precision of 3.5 microradians (or 7 microns radius at 2m from the interaction point).

\(\Rightarrow\) This is the precision on the position of the detector,
\(\Rightarrow\) this is not the precision of the detector for a track, which can be worse.
\(\Rightarrow\) this can be implemented for the tracker or the EM calorimeter, or a fiducial detector in-between

Detector should be hermetic in acceptance region (no cracks)
some hard physics challenges at the Z peak run:

2. **Luminosity measurement** there is a similar requirement (at smaller angle) for the luminosity detector where the inner limit of the detector acceptance should be known to 1 micron at 1m from IP.

3. **Stability of momentum measurement**
   this will affect the mass, width, asymmetry measurements which are sensitive to relative values of center-of-mass energies across the Z line shape, W pair threshold (ZH threshold and top threshold are less critical)

The magnetic field in the tracker should be stable, or monitored, with a precision of $\ll 10^{-6}$
Center-of-mass energy will be obtained from resonant depolarization with a precision of $10^{-6}$.
Small changes with respect to the common scale affect the measurements and one tries to detect them by measuring the average ECM with muon pairs.

Can one monitor the magnetic field with this precision? The absolute value is not so important, but the value should remain unchanged with that precision when changing (every few days to a week) center-of mass Energy by a few GeV back and forth.
4. flavour physics
everything having to do with b/c/gluon jet separation is of great interest for H and top physics. In addition the tau life time measurement with $1.5 \times 10^{11} \tau \tau$ events will give a GF measurement equivalent to that with muons (lepton universality test!)

This places a great premium on a **precision vertex detector**.

beam pipe size is 2cm in diameter.

Aim is to improve thickness considerably compared with LHC, radiation hardness is probably much less critical.

Compared with ILC:
1. power pulsing is impossible
2. but occupancy due to beam related backgrounds is enarly one order of magnitude lower.

5. **Particle identification is very relevant for flavour physics.**
Should cover energies from sub-GeV (TOF) up to $\sim 50$ GeV (CKOV, $dE/dx$)

**implementation without perturbing hermiticity is a challenge**
CONCLUSIONS

There is a large amount of work trying to find the elusive pointers to new physics by a two order of magnitude improvement in precision measurements.

We have a good idea of how to proceed and the interest by the theory community is remarkable, but still patchy.

We need to create the same awareness in the experimental community.

One of the upcoming tasks is to write-up the full overall picture and methodology in the EW working group.