Requirements on FCC-ee from the physics programme

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FCC week
28/6/21
Overview

• Run plan: why so many energy points, & why so much data?
• The compelling case for four interaction points
• $E_{CM}$ calibration: what is required, & what are implications for operation?
• Monochromotisation: the motivations for & challenges of a run at $E_{CM} = 125$ GeV
• The machine-detector interface, with some words on beampipe radius
FCC-ee: baseline run plan
(according to Conceptual Design Report)

Flexibility required (within reason) for order in which each sample is collected. Here discussion will proceed (mostly) ordered by $E_{\text{CM}}$ – this is not a proposal!
FCC-ee: baseline run plan

~150 ab\(^{-1}\) split between on-peak & off-peak over 4 years

E\(_{\text{CM}}\) calib. crucial

5 \times 10^{12} Z produced
Why 4 years and ~150 ab\(^{-1}\) at & around the Z pole?

With the discovery of the Higgs, all particles of the SM have now been found. Very precise measurements of their properties & behaviour, e.g. through electroweak observables at (& above) Z pole, will stress-test self-consistency of theory.

A rich array of measurements awaits, for example lineshape parameters:

\[
\begin{align*}
\text{LEP uncertainty} & & \text{Current FCC-ee estimate} \\
m_Z & 2200 \text{ keV} & 100 \text{ keV} \ (10^{-6} !) \\
\Gamma_Z & 2300 \text{ keV} & 25 \text{ keV} \ (10^{-5} !)
\end{align*}
\]

These measurements will unavoidably remain systematics limited (foreseen stat. uncertainty ~4 keV for both), but will require significant time and attention to get right.

Year-1 of Z run will not yield the final result!
Why 4 years and ~150 ab$^{-1}$ at & around the Z pole?

Lessons from history: a puzzling $E_b$ calibration test during 1993 resonance scan required second scan campaign in 1995 to understand...

...with full validation only coming in 1999.

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$E_{cm}$ [GeV]

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Physics requirements on FCC-ee

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Why 4 years and \( \sim 150 \text{ ab}^{-1} \) at \& around the Z pole?

Many Z observables have very small intrinsic experimental systematics, which will be further reduced, \& may become sub-dominant, with hard work \& data-driven studies. 

\textit{e.g.} forward-backward lepton asymmetries (on-peak \& off) \((A_{FB}^\|)\), lepton-to-hadron ratios \((R_l)\), tau-polarisation asymmetries \((A_{FB}^{pol, \tau})\), b-specific observables \((A_{FB}^b, R_b)\).

\[
A_{FB} \text{ for muons} \quad P_T \text{ vs. } \cos \theta_T \quad A_{FB} \text{ for b production}
\]
Why 4 years and ~150 ab\(^{-1}\) at & around the Z pole?

Excellent experimental control of off-peak di-muon asymmetry motivates campaign to collect 50-80 ab\(^{-1}\) off peak to gain highest sensitivity to Z-\(\gamma\) interference.

\[
A_{FB}^{\mu\mu}(s) \simeq \frac{3}{4} A_e A_\mu \times \left[ 1 + \frac{8\pi \sqrt{2} \alpha_{\text{QED}}(s)}{m_Z^2 G_F (1 - 4 \sin^2 \theta_W^\text{eff})^2} \frac{s - m_Z^2}{2s} \right]
\]

Allows for clean determination of \(\alpha_{\text{QED}}(m_Z^2)\), which is a critical input for \(m_W\) closure tests (see later).

relative \(\alpha_{\text{QED}}\) uncertainty with 80 ab\(^{-1}\)

This dependence, & location of half-integer spin tunes, guides the choice of off-peak energies: 87.8 & 93.9 GeV.

Goal: measure \(1/\alpha_{\text{QED}}(m_Z^2)\) to +/- 0.003.
Why $\sim 150 \text{ ab}^{-1} \at Z$? Flavour-physics opportunities

For a flavour physicist *more is never enough*! There are always important measurements that will remain statistics limited. Baseline will deliver a b sample that will be $x15$ Belle II ($+ B_s, B_c & \Lambda_b$) & *highly* complementary to LHCb upgrades.

A frequently shown plot, but one that’s very topical.

(However there are very nice more recent studies, *e.g.* $B_c \rightarrow \tau \nu$. See Tues parallel and [arXiv:2105.13330](https://arxiv.org/abs/2105.13330))

Unique possibilities at FCC-ee!

- Example of a measurement that LHCb can’t really do;
- $Z$ samples achievable at linear colliders (if any) will be too small for frontier b physics, in this mode or in almost any other.

However, no cause for complacency:

- Having smaller samples would be uncomfortable (& larger would be fantastic!) *c.f.* LHCb has $\sim 5000$ decays in the sister $B^0 \rightarrow K^*\mu\mu$ study [PRL 125 (2020) 011802].
Why $\sim 150 \text{ ab}^{-1} @ Z$? Flavour-physics opportunities

Tau physics leadership passed from LEP, to B factories, & then to Belle II. FCC-ee will deliver 3-4 x more taus than at Belle II, with equally clean environment & boost.

Outstanding opportunities to push lepton-universality tests in muons vs taus (essentially $G_F$ measurement with taus) to new frontier of precision!

Also probe for LFV in tau decay, e.g. $\tau \rightarrow \mu \mu \mu$ to $10^{-10}$ – very important in context of hints for lepton-universality violation in LHCb data & elsewhere.
Why $5 \times 10^{12} Z^0$s? Direct searches

FCC-ee will be a discovery machine, both through indirect searches (e.g. precision EW, Higgs and flavour physics), but also for direct searches for non-SM phenomena. e.g. 90% CL exclusion limits for heavy neutral lepton

FCC-ee Z-pole running will have enormous potential in searches for LFV decays, heavy sterile neutrinos, axion-like particles etc. In all cases integrated lumi is key!
FCC-ee: baseline run plan

- ~10 ab$^{-1}$ around threshold for $m_W$ over two years
- $E_{CM}$ calib. crucial
- $10^8$ WW produced

- ~0.20 ab$^{-1}$ around $tt$ threshold for $m_t$ over one year
Why 2 years and 12 ab$^{-1}$ at W$^+W^-$ threshold?

Threshold scan of 12 ab$^{-1}$, taken at 157.5 and 162.5 GeV will yield a statistical precision on $m_W$ of 0.5 MeV. Provided $E_{\text{CM}}$ can be controlled at similar, or better, level, this will give order of magnitude improvement on best hopes of LHC.

![Graph showing σ_{WW} vs √s (GeV)](image)

~10^8 W’s at FCC-ee

Data very valuable for other studies, e.g. $V_{cb}$ from flavour-tagged jets, $\alpha_{\text{QCD}}(m_W^2)$ from BRs… Furthermore Zγ return events will provide 10^{-3} determination of $N_\nu$. 

![ATLAS graph showing m_W precision](image)
Why measure $m_W$ to $\sim 0.5$ MeV?

Best possible precision on $m_W$ required to perform critical closure test on SM.

![Graph showing current status of $m_W$ and $m_t$ measurements.]

Note, it’s not only $m_W$ we need to improve, but also indirect prediction & also $m_t$. 

Physics requirements on FCC-ee
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Why measure $m_W$ to $\sim 0.5$ MeV?

Best possible precision on $m_W$ required to perform critical closure test on SM.

Current sensitivity on predicted value limited by auxiliary parameters.

$$m_W = 80.3584 \pm 0.0055_{m_{\text{top}}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{\text{QED}}}$$

$$= 80.358 \pm 0.008_{\text{total}} \text{ GeV},$$

All of these ($m_{\text{top}}, m_Z, \alpha_{\text{QED}}, \alpha_S, m_H$) will be greatly improved at FCC-ee!

Note, it’s not only $m_W$ we need to improve, but also indirect prediction & also $m_t$. 
Going to higher energies: $m_t$

$m_t$ known to $\sim 0.5$ GeV. Significant improvement needed for $m_W$ closure test.

Multi-point threshold scan with $20 \text{ fb}^{-1}$ / point will determine $m_t$ to $<20$ MeV
Status of closure test after Z programme, $W^+W^-$ and $t\bar{t}$ threshold scans
FCC-ee: baseline run plan

~5 ab$^{-1}$ at 240 GeV over three years
10$^6$ HZ produced and 25k WW→H

~1.5 ab$^{-1}$ at 365 GeV over four years, primarily for Higgs physics, but also valuable for top studies

200k HZ events
50k WW→H events
10$^6$ tt events
Why study Higgs at two energies?

Central goal of FCC-ee: model-independent measurement of Higgs width and couplings with (<)\% precision. Achieved through operation at two energy points.

5 ab\(^{-1}\) at 240 GeV
1\(^{0}\) HZ events
25k WW→H events

1.5 ab\(^{-1}\) at 365 GeV
200k HZ events
50k WW→H events

Sensitivity to both processes very helpful in improving precision on couplings.
Why study Higgs at two energies?

Central goal of FCC-ee: model-independent measurement of Higgs width and couplings with (\pm)\% precision. Achieved through operation at two energy points.

High precision achievable for all couplings; good complementarity to HL-LHC:

<table>
<thead>
<tr>
<th>Collider</th>
<th>HL-LHC</th>
<th>ILC_{250}</th>
<th>CLIC_{380}</th>
<th>LEP_{3240}</th>
<th>CEPC_{250}</th>
<th>FCC-ee_{240+365}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi (ab^{-1})</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>5_{240} + 1.5_{365} + HL-LHC</td>
</tr>
<tr>
<td>Years</td>
<td>25</td>
<td>15</td>
<td>8</td>
<td>6</td>
<td>7</td>
<td>3 + 4</td>
</tr>
<tr>
<td>$\delta_{\Gamma_H}/\Gamma_H$ (%)</td>
<td>SM</td>
<td>3.6</td>
<td>4.7</td>
<td>3.6</td>
<td>2.8</td>
<td>2.7</td>
</tr>
<tr>
<td>$\delta_{g_{123}/g_{123}}$ (%)</td>
<td>1.5</td>
<td>0.3</td>
<td>0.60</td>
<td>0.32</td>
<td>0.25</td>
<td>0.2</td>
</tr>
<tr>
<td>$\delta_{g_{123}/g_{123}}$ (%)</td>
<td>1.7</td>
<td>1.7</td>
<td>1.0</td>
<td>1.7</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>$\delta_{g_{123}/g_{123}}$ (%)</td>
<td>3.7</td>
<td>1.7</td>
<td>2.1</td>
<td>1.8</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>$\delta_{g_{123}/g_{123}}$ (%)</td>
<td>SM</td>
<td>2.3</td>
<td>4.4</td>
<td>2.3</td>
<td>2.2</td>
<td>1.7</td>
</tr>
<tr>
<td>$\delta_{g_{123}/g_{123}}$ (%)</td>
<td>2.5</td>
<td>2.2</td>
<td>2.6</td>
<td>2.1</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>$\delta_{g_{123}/g_{123}}$ (%)</td>
<td>1.9</td>
<td>1.9</td>
<td>3.1</td>
<td>1.9</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>$\delta_{g_{123}/g_{123}}$ (%)</td>
<td>4.3</td>
<td>14.1</td>
<td>n.a.</td>
<td>12</td>
<td>8.7</td>
<td>10.1</td>
</tr>
<tr>
<td>$\delta_{g_{123}/g_{123}}$ (%)</td>
<td>1.8</td>
<td>6.4</td>
<td>n.a.</td>
<td>6.1</td>
<td>3.7</td>
<td>4.8</td>
</tr>
<tr>
<td>$\delta_{g_{123}/g_{123}}$ (%)</td>
<td>3.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>BR_{EXO} (%)</td>
<td>SM</td>
<td>&lt; 1.7</td>
<td>&lt; 2.1</td>
<td>&lt; 1.6</td>
<td>&lt; 1.2</td>
<td>&lt; 1.2</td>
</tr>
</tbody>
</table>

Relative duration of 240 vs 365 GeV runs an interesting optimisation question in context of sensitivity to Higgs self coupling (see 2 IP vs 4 IP discussion).

Sensitivity to both processes very helpful in improving precision on couplings.
How many interaction points?

FCC-ee design as presented in CDR foresees two interaction points.
How many interaction points?

FCC-ee design as presented in CDR foresees two interaction points.

However, there are strong physics-driven arguments for evolving to a four interaction-point layout.

Key points (there are others):

- More data, sooner;
- Systematic robustness with redundancy;
- Better physics coverage.

We will restrict ourselves to a single example for each.
Why 4 IPs? More data, sooner

Key example: discovery of *trilinear Higgs coupling* essential for characterising Higgs potential. FCC-hh can measure it to better than +/-5% through double-Higgs prod. However, FCC-ee has indirect sensitivity through precise x-section measurements.

Baseline running strategy & 2 IPs gives +/- 42% on $\kappa_\lambda$, & +/- 34% with HL-LHC.

4 IPs both increases sample sizes, & allows initial stages of FCC-ee programme to be completed earlier, freeing up time for longer high-energy operation.

A very important lever (among several) for enabling discovery before FCC-hh!
Why 4 IPs? Systematic robustness

With only two experiments, important systematic effects risk being overlooked.

At LEP, it was inspection of 1991 individual \( m_Z \) results from each experiment that led to appreciation of effect of "RF sawtooth".[PLB 307 (1993) 187].

On a ring containing only L3 & OPAL (or ALEPH & DELPHI) this would have been much harder to spot.

<table>
<thead>
<tr>
<th>( m_Z ) [GeV]</th>
<th>91.160</th>
<th>91.170</th>
<th>91.180</th>
<th>91.190</th>
<th>91.200</th>
</tr>
</thead>
</table>

L3 before correction

ALEPH

OPAL

DELPHI

\( \Delta E_{\text{corr}} \) [MeV]: 12.7, 0.01, 12.8, -0.01
Why 4 IPs? Better physics coverage

Having four detectors allows for a wide range of technological solutions that can fully exploit wide and rich physics possibilities of FCC-ee programme.

e.g. for flavour physics require PID over wide momentum range and calorimetry with good energy resolution for soft $\pi^0$ reconstruction.

Such a design... ...great for this.... ...less good for this.
Requirements on $E_{CM}$ knowledge

Painstaking work required at LEP to ensure $E_{CM}$ knowledge was sufficient for flagship EW measurements. Even more stringent goals set at FCC-ee.

<table>
<thead>
<tr>
<th>Uncertainties from $E_{CM}$</th>
<th>LEP</th>
<th>FCC-ee (current estimate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z$</td>
<td>1.7 MeV</td>
<td>100 keV</td>
</tr>
<tr>
<td>$\Gamma_Z$</td>
<td>1.2 MeV</td>
<td>25 keV</td>
</tr>
<tr>
<td>$m_W$</td>
<td>9 MeV</td>
<td>300 keV</td>
</tr>
</tbody>
</table>

(Control of $E_{CM}$ at this level is also necessary to keep the associated systematic < statistical uncertainty for $\sin^2\theta_W$ from $A_{FB}$, $\alpha_{QED}(m_Z)$ & many other observables.)

What were the main challenges that existed at LEP?

• Precise measurement of $E_b$ through Resonant Depolarisation (RDP), but only in a few fills, before or after collisions. $E_{CM}$ knowledge limited by modelling of time evolution between measurements. FCC-ee requires a change of strategy!

• Beam polarisation not available at WW threshold, so RDP not possible. This problem should not exist at FCC-ee thanks to reduced energy spread.

* knowledge of $E_{CM}$ spread also plays a role for FCC-ee $\Gamma_Z$ & $\alpha_{QED}(m_Z^2)$
Some mechanisms of $E_b$ variation at LEP

$\Delta E_b = 10$ MeV ($\Delta C = 1$ mm)

Short- (tide) and long- (lake) term ring distortions.

NB at FCC-ee effects will be ~10x larger due to smaller momentum-compaction factor!

Rise of dipole fields due to stimulation from returning current from TGV.

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Requirements on $E_{CM}$ knowledge

$E_{CM}$ calib. must be a central consideration in FCC-ee design & operational strategy.

- RDP quasi-continuous: perform on pilot bunches for $e^-$ and $e^+$ several times an hour (overhead: for Z running need to spend ~1 hour at start of fill with wigglers on to allow polarisation to accumulate)
  → removes to 1st order all $E_b$ time-variation issues that plagued LEP.

- $f_{RF}$ change to keep beams centred in quadrupoles to suppress residual tidal effects on $E_b$; furthermore beam-beam offsets must be minimised to suppress dispersion-induced biases on $E_{CM}$.

- Investment in instrumentation & detailed logging of all machine parameters. Willingness to devote machine time to calibration studies (at LEP >50 full days taken in this manner from 1993 onwards).

Experiments must do their part: continual accumulation of $Z \rightarrow l^+l^-$ events enables relative energy changes, crossing angle, and energy spread to be monitored.
s-channel Higgs production and monochromatisation

An intriguing possibility, under evaluation and not in CDR baseline, is to devote a few years operation at $E_{\text{CM}}=m_H=125$ GeV to measure Yukawa coupling to electrons.

But cross-section is tiny…

…& effectively decreased further through ISR and because Higgs width ($\sim 4$ MeV) small compared to $E_{\text{CM}}$ spread.

Note that natural $E_{\text{CM}}$ spread for colliding beams is $\sim 100$ MeV. This must be reduced by $< 1/10$: the monochromatisation challenge!

Also need good knowledge of $m_H$ ($\sim \Gamma_H$), good $E_{\text{CM}}$ knowledge, & high $E_{\text{CM}}$ stability.
**The monochromatisation challenge**

Introduce horizontal dispersion and collide head on to reduce $E_{CM}$ spread.

Require crab cavities to achieve head-on collisions

Alternatively live without cavities, and rely on good vertex resolution to account for correlation between $x$ and $E_{CM}$.

(colour $\sim$ energy)
The monochromatisation challenge

However, dispersion increases horizontal emittance and reduces luminosity.

An interesting optimisation problem, when event rate is so low.
The monochromatisation challenge

Studies still underway – likely require several years to reach SM value at 3\(\sigma\). However, can do vastly better than any other machine. Also, motivation for 4 IPs!

Final remark: operation at \(E_{\text{CM}}=125\) GeV is also valuable for accumulating radiative returns to the Z and improving sensitivity to the number of neutrino families.
Machine-detector interface

Careful attention must be paid to MDI layout so as not to limit performance.

Agreed boundaries between machine & detector + conditions largely satisfactory:

- 2T solenoidal field at Z (possibility of 3T at higher energies under study)
- Low angle acceptance down to 100 mrad. This small value desirable because:
  - Minimises impact on energy-flow measurements;
  - Helps keep systematics manageable for high statistics cross-section measurements.
Beampipe radius

An item where gains can still be made is beampipe radius, as radius of first measured point is crucial in determining secondary vertex resolution.

CDR design with \( r_{bp} = 15 \text{ mm} \), and hence \( r_{\text{first}} \sim 17 \text{ mm} \), will limit performance.

- Probably OK for \( B_s \) physics
- But almost certainly not for reconstruction of decays with neutrinos via vertex constraints
- And probably limits charm tagging

\[ B^0_s \rightarrow D_s^- \pi^+ \]
\[ \bar{B}^0_s \rightarrow D_s^- \pi^+ \]

\[ B^0 \rightarrow K^+\pi^- \]
Assumes \( \sigma_{\text{sec}} \sim 7 \mu \text{m} \)

\[ LHCb, \text{ arXiv:2104.04421} \]

\[ 	ext{Monteil, arXiv:2106.01259} \]

\[ [\text{Gouskos & Selvaggi, FCCee Phys Perf meeting, 19/10/20}] \]
Beampipe radius

Variation in secondary-vertex resolution vs $r_{\text{first}}$, for two different decays [Donal Hill]:

$B_s \rightarrow J/\psi \phi$  
$3 \mu m$ hit precision

$B_s \rightarrow D_s K$  
$3 \mu m$ hit precision

News since CDR: updated MDI design incorporating $r=10$ mm beampipe (see Boscolo et al., arXiv:2105.09698). This is an extremely welcome development! Let’s continue dialogue to optimise performance.
Summary

• Very high luminosities available at FCC-ee over a wide range of energies present enormous discovery potential, through indirect means (i.e. super precise measurements of EW, Higgs and flavour observables) and through direct searches;

• There is a growing conviction that four interaction points will add robustness and breadth to the physics programme;

• The opportunity for precise knowledge $E_{CM}$ is a huge asset, and must be intrinsic to machine design and operation plans;

• The merits of an $e^+e^- \rightarrow H$ run are under evaluation. Interest challenges for monochromitisation vs luminosity and ECM calibration;

• The current MDI design is generally good for physics; we welcome continued progress in reducing the beampipe radius, exploring 3T option for high-energy operation, suppressing beam-related backgrounds etc.
Backups
Expected uncertainty contour for S & T parameters

Constraints on S & T parameters from global fit to EW precision observables.

With naïve estimate of future experimental and systematic uncertainties. Including statistical and parametric uncertainties only.