FCC-ee status

Michael Koratzinos
on behalf of the FCC study
Contents

• Where we are now / Physics motivation / Why circular?
• The FCC study
• The accelerator (emphasis on improvements/mitigations of newly discovered effects)
• The interaction region
• Polarization issues
• Physics highlights

Indebted to all my colleagues at FCC-ee and specifically to M. Benedikt, A. Blondel, P. Janot, K. Oide, D. Shatilov, F. Zimmermann for the liberal use of material.
Physics Motivation/
Circular Colliders
The butterfly plot

- The Standard Model is not a complete theory!
- New tools are needed to unravel nature’s mysteries
- $e^+e^-$ colliders are discovery machines
- Figure of merit for all colliders: energy vs luminosity
The strategy behind circular $e^+e^-$ colliders

• Measure accurately as many parameters which are sensitive to new physics as possible

• Caution: need to have a measuring power which is better than the expected signal! For example: Higgs couplings: most extensions to the standard model predict deviations from the standard model of the order of 1%. It is imperative, therefore, to build a machine that can probe these quantities to order 0.1%
For example: predictions of 4D Composite Higgs Models ($f < 2$ TeV)

Expected relative precision on the HZZ and Hbb couplings

FCC-ee is 10 sigma from expected smallest deviation

The HL-LHC could measure a deviation in favourable scenarios, but will be unable to distinguish between models

Patrick Janot arXiv:1510.09056
Circular colliders: luminosity

• e+e- circular colliders cannot compete with linear colliders in terms of energy. But they can compensate in terms of luminosity

• (they also provide a tunnel that can be later used for a hadron machine! “energy upgrade”)

• To get maximum luminosity necessitates operating the machine at a new regime that was never reached before in circular machines: the beamstrahlung dominated regime. This effect comes on top of the already known beam-beam limit
Accelerator design/ Optics
The circular e+e- collider approach

For the high luminosities aimed at, the beam lifetimes due to natural physics processes (mainly radiative Bhabha scattering) are of the order of a few minutes – the accelerator is ‘burning’ the beams up very efficiently.

A “top-up” scheme (a la B factories) is a must.

- Booster ring the same size as main ring, tops up the main ring every ~O(10s)
- Main ring does not ramp up or down

What kind of luminosities can be achieved?
How big a ring needs to be?
How much power will it consume?
The maximum luminosity is bound by the total power dissipated, the maximum achievable beam-beam parameter, the bending radius, the beam energy, the amount of vertical squeezing $\beta_y^*$, and the hourglass effect, a geometrical factor (which is a function of $\sigma_z$ and $\beta_y^*$).

\[
\mathcal{L} = \text{const} \times \frac{P_{tot}}{E_0^3} \frac{\rho}{10\,\text{km}} \left(\frac{120\,\text{GeV}}{E_0}\right)^3 \left(\frac{\xi_y}{0.1}\right) \left(\frac{R_{hg}}{0.83}\right) \left(\frac{1\,\text{mm}}{\beta_y^*}\right) \text{cm}^{-2}\text{s}^{-1}
\]
Design brief for circular accelerators

• Each energy has different challenges, but key is maximizing the beam-beam parameter at all energies by reaching the beam-beam limit and beamstrahlung limits, if possible, at the same time.

• Opt for high momentum acceptance (>2% at high energies, ~1% sufficient at 45GeV).

• Opt for the smallest vertical emittance possible (around 1pm).

• Run beam-beam simulations to find optimal working point – theoretical luminosities might not be attainable due to instabilities.
Four accelerators in one

We are planning to run at beam energies of 45GeV (Z), 80GeV(W), 120GeV(H) and 365GeV(t). We are maximizing performance at each energy. Each energy has unique challenges.

**Z running:** the most challenging machine. Very high current (>1A), therefore needs a special RF system, Piwinski angle is small, so crab waist does not help too much.

**Top running:** the next most challenging machine. High RF voltage, high momentum acceptance for reasonable beam lifetimes.

**W, H running:** in between the two machines above.
Progress since last year

• Design made more solid, simulation studies, looking at details that were not addressed so far... evolution rather than revolution

• Useful meetings/workshops
  – FCC week Berlin
  – EPOL workshop CERN
  – FCC 2\textsuperscript{nd} Physics Workshop CERN (15-19 January 2018) preceded by a theory mini-workshop on precision EW and QCD calculations for FCC
Optics for FCC-ee: main design features

- Energy: 45 to 182.5 GeV / Circumference: 100 km / two interaction points (IPs)
- horizontal crossing angle of 30 mrad at the IP, and a crab-waist scheme with local chromaticity correction.
- Non-interleaved sextupole scheme in the arcs with hundreds of independent families for both phase advances.
- “tapering” of all magnets, which scales all fields of magnets except the solenoids with the local beam energy.
- An asymmetric layout near the interaction region which reduces the critical energy of SR shining on the detector to below 100 keV.
- Sufficient transverse/longitudinal dynamic aperture to assure adequate beam lifetime with beamstrahlung and top-up injection.
Optics changes since last year

- Biggest change: reduction of $\beta_x^*$ at the IP at Z, W, and H energies (down to 15 cm at the Z, mitigation of the coherent beam-beam instability) and changing the arc phase advance to 60/60° at Z, making the arc lattice compatible to both phase advances with the non-interleaved sextupole scheme
- Application of the twin aperture quadrupole scheme to reduce power consumption of quadrupole magnets.
- Optics fitted to a modified layout of the FCC-hh collider.
- Increased the beam energy at ttbar. Nevertheless, optimization of the IR design has REDUCED the maximum critical energy of photons close to the IP from 100 to 90 keV
- A better packing factor of dipoles in the arc
- Asymmetric momentum acceptance at ttbar
- Space was made available for an inverse Compton spectrometer
Top energy challenges

- Beamstrahlung (BS) is the dominant process that limits luminosity (by limiting beam lifetimes)
- Mitigation: Keep vertical emittance as low as possible (coupling as low as possible)
- Colliding bunches must have similar charges, otherwise BS blows up the weak bunch ➔ Bootstrapping is needed (also needed at low energies). Assumption: bunches are equal to +/-3%

Transverse force seen by electrons in the transverse plane. Due to the horizontal crossing angle, electrons experience all values in the horizontal plane; in the vertical plane, electrons at ~2 sigma onwards experience the highest transverse forces.
At low energies, an instability was encountered: above a certain bunch charge threshold, any asymmetry between colliding bunches would mean that the weak bunch would blow up.
Low energies: Coherent X-Z instability

This instability develops in the horizontal plane and it is manifested by a “wriggle” of the bunch shape. Results in horizontal emittance blowing up.

Horizontal centroid of the beam at different longitudinal slices: red: zero turns, green: 300 turns, blue: 1000 turns.

Horizontal emittance blows up.
Low energies: luminosity optimization

Mitigation: Both instabilities are associated with the growth of $\varepsilon_x$, therefore we have to reduce $\beta_x^*$ which means a decrease in both the normalized horizontal kick and $\xi_x$.

- Decrease $\beta_x^*$ to 15cm. This requires longitudinal slicing of QC1
- Increase bunch length; ➔ for this we need to increase the momentum compaction factor; ➔ for this we need to change optics to 60/60 (from 90/90), also decrease RF voltage
- “bootstrapping” necessary

M. Koratzinos, IAS2018, HKUST, Hong Kong, 22 January 2018.
Instabilities are such that the two colliding bunches must have similar intensities so that the emittance of the weak beam does not blow up.

- How do we fill the machine up then?
- “bootstrapping” fill each bunch with $5 \times 10^9$ electrons (positrons) at a time
- Technique demonstrated to work well

D. Shatilov
Intermediate energies: WW and ZH

• As the energy increases, the bunch lengthening and Piwinski angle decrease, while the damping decrements grow. Hereby both instabilities visible at the Z weaken.

• the lattice optimization is performed for the selected $\beta_x^*$ (and $\beta_y^* = 1$ mm) in order to maximize the dynamic aperture and energy acceptance ($\eta$); hereby we obtain $\eta$ (namely, 1.3% and 1.5%).
Optics - dynamic aperture (longitudinal)

(a) $Z \pm 1.3\%$

(b) $W \pm 1.3\%$

(c) $Z_h \pm 1.5\%$

(d) $t\bar{t} -2.8 \pm 2.4\%$
Dynamic aperture - transverse
International FCC collaboration (CERN as host lab) to study:

- **$pp$-collider ($FCC-hh$)** → main emphasis, defining infrastructure requirements
- **$\sim 100$ km tunnel infrastructure** in Geneva area, site specific
- **$e^+e^-$ collider ($FCC-ee$)**, as potential first step
- **HE-LHC** with $FCC-hh$ technology
- **$p-e$ ($FCC-he$) option**, IP integration, $e^-$ from ERL

$\sim 16\ T \Rightarrow 100\ TeV\ pp\ in\ 100\ km$
FCC study: physics and performance targets

**FCC-ee:**
- Exploration of 10 to 100 TeV energy scale via couplings with precision measurements
- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass) \( (m_Z, m_W, m_{top}, \sin^2 \theta_w^{\text{eff}}, R_b, \alpha_{\text{QED}}(m_Z), \alpha_s(m_Z,m_W,m_t)) \), Higgs and top quark couplings
  - Machine design for highest possible luminosities at \( Z, WW, ZH \) and \( tt\bar{t} \) working points

**FCC-hh:**
- Highest center of mass energy for direct production up to 20 - 30 TeV
- Huge production rates for single and multiple production of SM bosons (\( H,W,Z \)) and quarks
  - Machine design for 100 TeV c.m. energy & integrated luminosity \( \sim 20\text{ab}^{-1} \) within 25 years

**HE-LHC:**
- Doubling LHC collision energy with FCC-hh 16 T magnet technology
- c.m. energy = 27 TeV \( \sim 14 \text{ TeV} \times 16 \text{ T}/8.33\text{T} \), target luminosity \( \geq 4 \times \text{HL-LHC} \)
  - Machine design within constraints from LHC CE and based on HL-LHC and FCC technologies

M. Benedikt
## FCC-ee machine parameters - Dec 2017

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>W</th>
<th>H (ZH)</th>
<th>ttbar</th>
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<tbody>
<tr>
<td>beam energy [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
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<td>arc cell optics</td>
<td>60/60</td>
<td>90/90</td>
<td>90/90</td>
<td>90/90</td>
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<td>emittance hor/vert [nm]/[pm]</td>
<td>0.27/1.0</td>
<td>0.28/1.0</td>
<td>0.63/1.3</td>
<td>1.46/2.9</td>
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<td>beta* horiz/vertical [m]/[mm]</td>
<td>0.15/.8</td>
<td>0.2/1</td>
<td>0.3/1</td>
<td>1/2</td>
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<td>total RF voltage [GV]</td>
<td>0.10</td>
<td>0.4</td>
<td>2.0</td>
<td>10</td>
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<td>energy acceptance [%]</td>
<td>±1.3</td>
<td>±1.3</td>
<td>±1.5</td>
<td>-2.8+2.4</td>
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<tr>
<td>energy spread (SR / BS) [%]</td>
<td>0.038/0.132</td>
<td>0.066/0.153</td>
<td>0.099/0.151</td>
<td>0.147/0.192</td>
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<tr>
<td>bunch length (SR / BS) [mm]</td>
<td>3.5 / 12.1</td>
<td>3.3 / 7.65</td>
<td>3.15 / 4.9</td>
<td>2.45 / 3.25</td>
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<td>bunch intensity $[10^{11}]$</td>
<td>1.7</td>
<td>2.3</td>
<td>1.8</td>
<td>3.3</td>
</tr>
<tr>
<td>no. of bunches / beam</td>
<td>16640</td>
<td>1300</td>
<td>328</td>
<td>33</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>5.4</td>
</tr>
<tr>
<td>luminosity $[10^{34} \text{ cm}^{-2}\text{s}^{-1}]$</td>
<td>&gt;200</td>
<td>&gt;30</td>
<td>&gt;7</td>
<td>&gt;1.5</td>
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<tr>
<td>luminosity lifetime [min]</td>
<td>70</td>
<td>30</td>
<td>20</td>
<td>20</td>
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<tr>
<td>allowable asymmetry [%]</td>
<td>±5</td>
<td>±3</td>
<td>±3</td>
<td>±3</td>
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</table>
FCC-ee and CEPC: 2 IPs
ILC and CLIC: 1 IP
Civil Engineering schedule study

- CE & schedule studies with consultants
- first sectors available after 4.5 to 5 years for Technical Infrastructure installation
- total CE duration ~7 years

M. Benedikt
schedule constrained by 16 T magnets & CE → earliest possible physics starting dates
- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)
recall the construction of LEP

<6 years from zero to physics

E. Picasso
H. Schopper

1984
1985
1986
1987
1988
1989
CDR summary volumes will be available by end 2018, as input for European Strategy Update 2019/20
Optimisation in view of accessibility surface points, tunneling rock type, shaft depth, etc. optimum: **97.5 km**

NB: 97.5 km cheaper than 80 km!

**Tunneling**
- Molasse 90% (good rock),
- Limestone 5%, Moraines 5% (tough)

**Shallow implementation**
- ~ 30 m below Léman lakebed
- Reduction of shaft lengths etc...
- One very deep shaft F (476m) (RF or collimation), alternatives being studied, e.g. inclined access
FCC: Common layouts for \( ee \) and \( hh \)

1. **FCC-hh**
   - L, A, B
   - Exp. + Inj.
   - L_DS, L_sep, L_arc
   - 1.4 km

2. **FCC-ee**
   - IP, 30 mrad
   - FCC-hh/ee Booster
   - 9.4 m
   - Lepton beams cross over (top energy: common RF) to enter the IP from inside.

3. Two main IPs in A, G for both machines

4. Asymmetric “moustache” IR idea by A. Blondel, implemented by K. Oide

5. Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for \( \pm 1.2 \) km.

Key: FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)
Experimental caverns

Sharing the FCC experimental caverns
(Preliminary layout)
FCC tunnel integration

FCC-ee

FCC-hh

5.5 m diameter

V. Mertens

M. Benedikt
SuperKEKB: an FCC-ee demonstrator

$I_{e^+}=3.6 \, A, \, I_{e^-}=2.6 \, A$

$P_{\text{SR}} \sim 13 \, \text{MW}$

$C = 3 \, \text{km}$

beam commissioning started this year

**top up injection at high current**

$\beta_y^* = 300 \, \mu\text{m} \, (\text{FCC-ee: } 1 \, \text{mm})$

**lifetime** 5 min (FCC-ee: $\geq 20$ min)

$\varepsilon_y/\varepsilon_x = 0.25\%$ (similar to FCC-ee)

**off momentum acceptance** ($\pm 1.5\%$, similar to FCC-ee)

$e^+$ production rate (2.5x$10^{12}$/s, FCC-ee: $<1.5x10^{12}$/s (Z cr.waist))

SuperKEKB goes beyond FCC-ee, testing all concepts

K. Oide et al.
RF system requirements

Very large range of operation parameters

- Voltage and beam current ranges span more than factor $> 10^2$
- No efficient single RF system solution satisfies the requirements

“Ampere-class” machines

<table>
<thead>
<tr>
<th></th>
<th>$V_{\text{total}}$ GV</th>
<th>$n_{\text{bunches}}$</th>
<th>$I_{\text{beam}}$ mA</th>
<th>$\Delta E/\text{turn GeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC-hh</td>
<td>0.032</td>
<td></td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>0.4/0.2</td>
<td>30000/90000</td>
<td>1450</td>
<td>0.034</td>
</tr>
<tr>
<td>W</td>
<td>0.8</td>
<td>5162</td>
<td>152</td>
<td>0.33</td>
</tr>
<tr>
<td>H</td>
<td>5.5</td>
<td>770</td>
<td>30</td>
<td>1.67</td>
</tr>
<tr>
<td>t</td>
<td>10</td>
<td>78</td>
<td>6.6</td>
<td>7.55</td>
</tr>
</tbody>
</table>

“high gradient” machines

O. Brunner, A. Butterworth, R. Calaga,...
RF system R&D lines

400 MHz single-cell cavities preferred for hh and ee-Z (few MeV/m)

- Baseline Nb/Cu @4.5 K, development with synergies to HL-LHC, HE-LHC
- R&D: power coupling 1 MW/cell, HOM power handling (damper, cryomodule)

400 or 800 MHz multi-cell cavities preferred for ee-H, ee-tt and ee-W

- Baseline options 400 MHz Nb/Cu @4.5 K, 800 MHz bulk Nb system @2K
- R&D: High Q₀ cavities, coating, long-term: Nb₃Sn material

A possible scenario - evolving

O. Brunner, A. Butterworth, R. Calaga

M. Koratzinos, IAS2018, HKUST, Hong Kong, 22 January 2018.
A very important power consumption (and cost) driver is the klystron efficiency. For many years this has stagnated at ~65%. This translates to a power consumption by the RF system alone of ~200MW.

2014 breakthrough in klystron theory:

- “congregated bunch” V.A. Kochetova, 1981
- “BAC” method [I.A. Guzilov, O.Yu. Maslennikov, A.V. Konnov 2013]

These three methods together promise a klystron efficiency ~90%

An international collaboration “HEIKA” (CERN, ESS, SLAC, CEA, MFUA, Lancaster U, Thales, JS, CPI, VDBT) is now designing, building and testing prototypes. Simulations and first hardware tests extremely encouraging.

E. Jensen, I. Syratchev, C. Lingwood

M. Koratzinos, IAS2018, HKUST, Hong Kong, 22 January 2018.
FCC-ee dual aperture main magnets

low-power low-cost designs - factor 2 power saving by dual aperture

dipole

17 MW at 175 GeV

A/ bus bar

300 mm

450 mm

0 0.5 T 1.0 T

quadrupole

22 MW at 175 GeV with Cu coil

magnetic measurements ongoing

M. Benedikt

A. Milanese

construction of main dipole and quadrupole models (~1 m units)
### FCC-ee total power

| subsystem                        | Z  | W  | ZH | t̅t̅ | LEP2  
|----------------------------------|----|----|----|------|-------
| collider total RF power      | 163| 163| 145| 145  | 42    
| collider cryogenics            | 2  | 5  | 23 | 39   | 18    
| collider magnets               | 3  | 10 | 23 | 50   | 16    
| booster RF + cryo              | 4  | 4  | 6  | 7    | -     
| booster magnets                | 0  | 1  | 2  | 5    | -     
| injector complex               | 10 | 10 | 10 | 10   | <10   
| physics detectors (2)          | 10 | 10 | 10 | 10   | 9     
| cooling & ventilation**        | 47 | 49 | 52 | 62   | 16    
| general services               | 36 | 36 | 36 | 36   | 9     
| **total**                      | 275| 288| 308| 364  | 120   

For comparison, total CERN complex in 1998 used up to 237 MW

**private discussions with M. Nonis**

*dividing total energy used by 200 days*
CERN energy consumption

FCC-ee estimate
~300MW × 200days = 1.4TWh

S. Claudet - CERN
Procurement Strategy

3rd Energy Workshop 29-30 October 2015
electricity cost

facility electricity cost 2014/15 in Euro / MWh

1400 GWh / yr → ~70 MEuro / yr

Courtesy: M. Seidel, EuCARD-2, V. Shiltsev, K. Oide, Q. Qin, G. Trubnikov, and others
MDI and polarization
FCC-ee MDI optimization

This is a very demanding, interdisciplinary problem. Good progress has been made.

Beam pipe radius at IP is 15mm

M. Koratzinos, IAS2018, HKUST, Hong Kong, 22 January 2018.
Design of magnetic elements around the IR

X-Y view – looking towards the IP

Beam pipes

Luminosity counter

Compensating solenoid

Screening solenoid

Final focus quads

CCT final focus quads

M. Koratzinos, IAS2018, HKUST, Hong Kong, 22 January 2018.
The compensation scheme

Vertical emittance blow-up <0.3pm for two IPs
The final focus quadrupole system

Excellent field quality
fully compensated very
compact design

Magnetic design

3D printed prototype

CAD drawing

Corrector detail
The first two turns of the quadrupole contain, apart from the B2 component, all the necessary components to nullify the edge effects.
**Crosstalk compensation**

QC1L1 quadrupole, length = 720mm distance at tip: 66mm, angle 30mrad, powered together

**Before compensation**

**After compensation**

After compensation: all multipoles under 0.1 units (limited by alignment errors, not included here)
Measuring the beam energy and energy spread

• Measuring the beam energy and energy spread is essential at the Z and W running.

• We aim for errors of ~100keV for ECM. Use the resonant depolarization method (transverse polarization needed)
  – Note that statistical error for the Z mass determination is only 5keV ($5.10^{12}$ Zs!)
  – Also note that the daily variation of the energy due to terrestrial tides would be ~130MeV
  – LEP experience: $M_z$ measured to 2MeV

• A working group has been set up (chaired by A. Blondel) and a workshop was organised at CERN

• Please note that measuring the beam energy necessitates the use of dedicated hardware, so it needs to be designed early.
The resonant depolarization method

\[ \nu = \frac{\alpha \gamma}{mc^2} = \frac{E[\text{MeV}]}{440.6486(1)[\text{MeV}]} \]

- The spin tune of an electron in a storage ring, \( \nu \), is proportional to its energy.
- This energy can be measured (instantaneously) to \(~100\text{keV per beam}!\)
- Different effects change the beam energy by orders of magnitude larger than that!
- We have the LEP experience to assist us, but still need to do a factor 20 better than that.
- Unique to FCC-ee: the resonant depolarization method can be used not only for the running around the Z, but also for the WW running

**Unique to circular colliders**

At the Z, polarization times are high (200 hours) – use dedicated wigglers

Transverse polarization of a few % is sufficient for a measurement – every 5 mins / both beams

Careful machine preparation + harmonic bump tuning
Achieving polarization

Accurate energy determination is needed for: $M_Z$, $\Gamma_Z$, $M_W$, $sin^2\theta_W$ (from the muon F-B asymmetry at the Z)

- To depolarize you must first have achieved polarization; ~10% polarization sufficient
- A real (imperfect) machine depolarizes fast – need careful corrections to restore polarization levels
- Would this be possible? Simulation code SISTROS says yes both for the Z and for the W. Correcting an imperfect machine (quad misalignments + BPM errors) restores polarization levels.

Excellent polarization at the Z (but slow)

Energy spread increases $\sigma_{Eb} \propto E_b^{2/\rho}$ and polarization level decreases.

At the W expectation similar to LEP at Z

→ enough for energy calibration

E. Gianfelice-Wendt
Efficient polarimeters (one for each beam) are needed.

Backscattered Compton $\gamma + e \rightarrow \gamma + e$  
$\gamma$ from 532 nm (2.33 eV) laser – successive shorts oppositely polarized

The scattered electron contains anti-correlated information on e-beam polarization and gives information on beam energy.

Practical arrangement similar to LEP for the detection of the photon, but complemented with an electron spectrometer.

N. Muchnoi
it is expected that beam polarization can be measured to $P \pm 1\%$ (absolute) in a few seconds. (if the level is 5%, this is 5$\sigma$).
At the Z peak we collect $10^6 \mu\mu$ events every 5 minutes. Their kinematics is affected by:
- energy spread
- $e^+$ vs $e^-$ energy difference.

P. Janot has shown that indeed both can be determined with extremely good precision with these events.

The energy difference is an important ingredient in understanding the RF model.
FCC-ee detectors

Two integration, performance and cost estimates ongoing:
-- Linear Collider Detector group at CERN has undertaken to adapt the CLIC-SID detector for FCC-ee
-- new IDEA, detector specifically designed for FCC-ee (and CEPC)

“CLIC-detector revisited”

“IDEA”

- Vertex detector: ALICE
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke

A. Blondel
Physics highlights
### FCC-ee possible operation model

<table>
<thead>
<tr>
<th>Working point</th>
<th>Luminosity/IP ([10^{34} \text{ cm}^{-2}\text{s}^{-1}])</th>
<th>Total luminosity (2 IPs)/yr</th>
<th>Physics goal ([\text{ab}^{-1}])</th>
<th>Run time [years]</th>
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<tr>
<td>Z first 2 years</td>
<td>100</td>
<td>26 ab(^{-1})/year</td>
<td>150 ab(^{-1})</td>
<td>4</td>
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<tr>
<td>Z later</td>
<td>200</td>
<td>52 ab(^{-1})/year</td>
<td></td>
<td></td>
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<tr>
<td>W</td>
<td>32</td>
<td>8.3 ab(^{-1})/year</td>
<td>10 ab(^{-1})</td>
<td>1</td>
</tr>
<tr>
<td>H</td>
<td>7.0</td>
<td>1.8 ab(^{-1})/year</td>
<td>5 ab(^{-1})</td>
<td>3</td>
</tr>
<tr>
<td>Machine modification</td>
<td></td>
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<tr>
<td>(RF installation &amp;</td>
<td></td>
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<tr>
<td>rearrangement)</td>
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<tr>
<td>Top 1st year (350 GeV)</td>
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<td>0.2 ab(^{-1})/year</td>
<td>0.2 ab(^{-1})</td>
<td>1</td>
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<td>Top later (365 GeV)</td>
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<td>0.38 ab(^{-1})/year</td>
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<td>4</td>
</tr>
</tbody>
</table>

**Total program duration:** 14 years - *including machine modifications*

**Phase 1 \((Z, W, H)\):** 8 years,  
**Phase 2 (top):** 6 years

M. Benedikt
FCC-ee discovery potential

Today we do not know how nature will surprise us. A few things that FCC-ee could discover:

WILL EXPLORE the 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)
  \( m_Z, m_W, m_{\text{top}}, \sin^2 \theta_{\text{w eff}}, R_b, \alpha_{\text{QED}}(m_z) \alpha_s(m_z m_W m_\tau), \) Higgs and top quark couplings

COULD DISCOVER a violation of flavour conservation or universality
  for example FCNC (\( Z \rightarrow \mu\tau, e\tau \)) in \( 5 \times 10^{12} \) \( Z \) decays.
  + flavour physics (\( 10^{12} \) \( \text{bb} \) events) (\( B \rightarrow s \tau \tau \) etc.)

COULD DISCOVER dark matter as an «invisible decay» of H or Z or in LHC loopholes.

COULD DISCOVER very weakly coupled particles in the 5-100 GeV energy scale
  such as: Right-Handed neutrinos, Dark Photons etc...

+ an enormous amount of clean, unambiguous work on QCD etc....

⇒ NB the «Z factory» plays an important role in the ‘discovery potential’

See M. Bicer et al., “First Look at the Physics Case of TLEP,” JHEP01 (2014) 164

A. Blondel
Physics goals at the Z pole

- Precision EW measurements with a Z resonance scan: 2 years
  - Lineshape
    - $m_Z, \Gamma_Z$ to $< 100$ keV (Current)
    - $\sqrt{s}$ precision, luminosity accuracy, higher-order theory predictions
  - Asymmetries
    - $\sin^2\theta_W$ to $6 \times 10^{-6}$
      - $\alpha_{QED}(m_Z)$ to $3 \times 10^{-5}$
  - Branching ratios, $R_l, R_b$
    - $\alpha_S(m_Z)$ to 0.0002
      - $R_l$ to 0.002 (Current)

- Most measurements are systematics-limited after the first (couple) year(s) ($\sim 10^{12}$ $Z$)
  - $\sqrt{s}$ precision, luminosity accuracy, higher-order theory predictions

  BUT

- Severe limitation comes from the knowledge of $\alpha_{QED}(m_Z)$ (see next slide)
  - Direct measurement possible with two more years at $\sqrt{s} = 87.9$ and 94.3 GeV

- A sample of $10^{13}$ $Z$ (two more years) opens a large variety of interesting possibilities
  - Discovery new physics with rare $Z$ (visible or invisible) decays
  - Discovery new physics with $b, c, \tau$ rare decays ($Z \rightarrow bb, cc, \tau\tau$)

- A few years at the Z makes the link between the intensity and the energy frontiers
Statistics needed at/around the Z pole

Although many measurements are dominated by systematic uncertainties with $10^{12}$ Zs, some crucial measurements / discovery channels need more statistics.

**Example:** measurement of $\alpha_{\text{QED}}(m_Z)$ from $A_{FB} (\mu\mu)$ through $\gamma/Z$ interference

- With 40 ab$^{-1}$ at 87.9 GeV and 40 ab$^{-1}$ at 94.3 GeV (two years in total)
- $\Delta\alpha/\alpha \sim 3 \times 10^{-5}$ (stat); Most syst. exp. uncertainties cancel in the combination
  
  Beam energy calibration $\sim 10^{-5}$ (dominant experimental uncertainty)
  
  A knowledge of the beam energy spread to 5-10% would help

- Similar statistics needed for most asymmetries at / around the Z pole

---

P. Janot, eeFACT2016, Daresbury

M. Koratzinos, IAS2018, HKUST, Hong Kong, 22 January 2018.
Physics goals at the WW threshold

- **Within ~1 year at the WW threshold**
  - **Threshold scan**
    - \( m_W \) to < 500 keV (15 MeV)
  - **Branching ratios** \( R_{l\nu}, R_{\text{had}} \)
    - \( \alpha_S(m_W) \) to 0.0002 (0.002)
  - **Radiative returns** \( e^+e^- \rightarrow \gamma Z \)
    - \( N_\nu \) to 0.0004 (0.008)

- This \( m_W \) precision is essential for the full exploitation of the Z precision measurements

**Prediction from Z measurements after the FCC-ee**

\[
m_W = 80.3593 \pm 0.0001 (m_{\text{top}}) \pm 0.0001 (m_Z) \pm 0.0003 (\alpha_{\text{QED}}) \\
\quad \pm 0.0002 (\alpha_S) \pm 0.0000 (m_H) \pm 0.0004 (\text{theo.}) \\
= 80.3593 \pm 0.0005 \text{ GeV} \quad (\text{~precision of direct measurement})
\]

- With similar systematic limitations as at the Z pole
  - E.g., higher-order theory predictions (order of magnitude improvement)

And also:
- TGC / QCG
- Rare W decays
A note on attainable precision

Example: the W mass

Prediction:

$\frac{m_W = 80.3593 \pm 0.0001}{m_{\text{top}}} \pm 0.0001 \quad (m_Z) \pm 0.0003 \quad (\alpha_{\text{QED}}) \\
\pm 0.0002 \quad (\alpha_s) \quad \pm 0.0000 \quad (m_H) \pm 0.0040 \quad (\text{theo.})$

before FCC

After FCC

direct measurement:

$m_W = 80.385 \pm 0.0005$

Essential to reduce theory error: necessitates calculation up to 3-4 loops. Effort has already started. 2 loop calculations finished – 3 loops started. Workshop at CERN 12-13 January 2018 to kickstart this

If only one ingredient is missing, the sensitivity to new physics may entirely vanish.
Physics goals at and above the top threshold

- **Primary goal**: precise $m_{\text{top}}$ measurement at threshold
  - Essential for full harnessing of Z & W precision data
    - 10 MeV precision (stat.) reached with 0.2 ab$^{-1}$
  - Benefits from $\alpha_s$ measurement at lower $\sqrt{s}$
    - QCD higher orders: dominant syst. (30 MeV)
  - Also from threshold scan:
    - Top decay width, top Yukawa coupling

- **Many interesting opportunities slightly above threshold (365 GeV)**
  - Top EW couplings, $t\bar{t}\gamma$ and $t\bar{t}Z$, to 1%
    - Sensitive to new physics
    - Synergetic with FCC-hh for $t\bar{t}H$ Yukawa coupling measurement
  - Anomalous top production and decay
  - Higgs decay width to 1%
  - ...

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Patrick Janot

FCC Week, Berlin

29 May - 2 June 2017

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F. Simon

Statistical precision of $\sigma_{WW \rightarrow H} \times \text{BR}(H \rightarrow bb)$

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>TLEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>240 - 250</td>
<td>2.2%</td>
</tr>
<tr>
<td>350</td>
<td>0.6%</td>
</tr>
</tbody>
</table>
Higgs couplings

$g_{Hxx}$ precision:

<table>
<thead>
<tr>
<th>Couplings</th>
<th>FCC-ee</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>0.15%</td>
<td>-</td>
</tr>
<tr>
<td>WW</td>
<td>0.20%</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>1%</td>
<td>-</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>1.5%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>--</td>
<td>1%</td>
</tr>
<tr>
<td>$tt$</td>
<td>13%</td>
<td>1%</td>
</tr>
<tr>
<td>$bb$</td>
<td>0.4%</td>
<td>-</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>0.5%</td>
<td>-</td>
</tr>
<tr>
<td>$cc$</td>
<td>0.7%</td>
<td>-</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>6.2%</td>
<td>2%</td>
</tr>
<tr>
<td>uu,dd</td>
<td>$H \rightarrow \rho \gamma?$</td>
<td>$H \rightarrow \rho \gamma?$</td>
</tr>
<tr>
<td>ss</td>
<td>$H \rightarrow \phi \gamma$?</td>
<td>$H \rightarrow \phi \gamma$?</td>
</tr>
<tr>
<td>ee</td>
<td>$ee \rightarrow H$</td>
<td>-</td>
</tr>
<tr>
<td>HH</td>
<td>30%</td>
<td>~3%</td>
</tr>
<tr>
<td>inv, exo</td>
<td>&lt;0.45%</td>
<td>$10^{-3}$</td>
</tr>
</tbody>
</table>

Important remark: for FCC-hh, we need to either assume the standard model with no deviations, or the measurements obtained at FCC-ee.

The combination of FCC-ee and FCC-hh is «invincible».
Global Fit and sensitivity to new physics

- Combining all EW measurements
  - In the context of the SM... and beyond

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i \]

Without \( m_Z (\alpha_{\text{EQ}}) \) @ FCC-ee, the SM line would have a 2.6 (1.8) MeV width. FCC-ee sensitivity severely drops without POLARIZATION + STATISTICS (and improved theory calculations)

Today: \( \Lambda > 5-10 \) TeV

After FCC-ee: \( \Lambda > 50-100 \) TeV?

Synergetic with FCC-hh

J. Ellis and P. Janot
FCC-ee sensitivity to heavy RH neutrinos

Simulation of heavy neutrino decay in a FCC-ee detector

Simple an unambiguous signature – offset vertex
Sterile neutrino sensitivity

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh**: LFV signatures and displaced vertex search
  - **FCC-eh**: LFV signatures and displaced vertex search
  - **FCC-ee**: Indirect search via EWPO and displaced vertex search

![Graph showing sterile neutrino sensitivity](image)

- **FCC-hh** able to test all flavour combinations.
- Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.
- Good sensitivity reach from FCC-hh & FCC-eh.
The link to FCC-hh

The synergy between FCC-ee and FCC-hh could be another talk! (cf A. Blondel, Lepton photon, Aug 2017, Guangzhou, China [http://indico.ihep.ac.cn/event/6183/])

Having FCC-ee followed by FCC-hh makes sense:
- Smoothens out the spending profile – both machines share the same tunnel and a lot of infrastructure
- For FCC-ee: it gives a chance for a discovery in case that precision measurements show deviations from the SM
- For FCC-hh: it makes it affordable

This has worked perfectly in the past!
Summary

- FCC-ee is a state-of-the-art e+e- collider pushing the frontiers regarding performance.
- FCC-ee offers extremely high luminosities in the energy range from Z to ttbar.
- FCC-ee offers precise energy calibration at the Z and W energies.
- FCC-ee technology is ready; ongoing R&D aims at further increasing efficiency.
- Optics fulfills all requirements, baseline luminosity performance is predicted with confidence.

- FCC-ee has an excellent physics potential and can constrain the standard model by improving dramatically on EW parameters.
- It will measure the Higgs couplings to a precision 0.1% to 1%.
- It can put limits on the energy scale of new physics to some 10s of TeV.
- The combination of FCC-ee and FCC-hh maximizes physics reach.
Thank you