The Future Circular Colliders (FCC) Feasibility Study and its Physics Potential

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Why do we need a new accelerator after the LHC?

The FCC Feasibility Study

The FCC-ee Physics potential

Next steps
Particle physics appears as a mature branch of fundamental science

The ‘Standard Model’ appeared in 1976 after the discoveries of
- Neutrino Neutral currents (Z boson exchange) in 1973 and
- Charmed particles (BNL, SLAC) in 1974-76

since then we have been discovering all the particles that have electric charge or QCD charge, or weak isospin (SM couplings), and the Higgs boson, by increasing accelerator energies.

The Standard Model is “complete” and explains all HEP Physics, but..
What is Dark matter?

Standard Model particles constitute only 5% of the energy in the Universe.

Where is primordial antimatter gone?

What is the origin of neutrino masses?

Not a unique solution in the SM

- Dirac masses (why so small?) or Majorana (why not Dirac?)
- Heavy right-handed neutrinos?
- «Sterile», very small coupling to known particles
  completely unknown masses (eV to ZeV), hence very difficult to find

... but could perhaps explain all: Dark Matter, Baryon Asymmetry, $\nu$-masses
It is a unique object, a scalar particle/field (spin 0), not a matter field, not a boson mediating a gauge interaction, but a field carrying a new type of interaction of the Yukawa type.

Many proposals for new accelerators to study it, and to study Beyond Standard Model (BSM) physics.

Easier choice on the machine now that the Higgs boson has been discovered.

Precise nature of the Higgs boson?

Origin of electroweak symmetry breaking (EWSB)?

Shape of the Higgs potential?

Strength of the electroweak phase transition? What is its role just after the big bang? Inflation?

We need to determine precisely the Higgs couplings and the Higgs self-couplings to answer these questions.
How to best study the Higgs / go beyond the Standard Model?

- By measuring deviations from precise predictions (ex: Higgs or Electroweak couplings...)
- By observing New Phenomena (ex: Neutrino Oscillations, CP violation..)
- By direct observation of new particles

But we do not have a natural energy scale to search for!

- We don’t know where to look and what we will find

- The next facility must have a reach as broad and powerful as possible,
  - more Sensitivity, more Precision, more Energy

Circular machines, thanks to synergies and complementarities between ee and hh, offers today the most versatile and adapted response to today’s physics landscape.
Motivation for a circular collider FCC-ee vs. a linear collider

One of the great advantages of the circular (e+ e-) colliders is:

- The possibility of using the same beams for many hours and serving several interaction points with net overall gain both in integrated luminosity and luminosity/MW.

FCC-ee is a machine with a very rich menu of physics possibilities, given its luminosity, and the options to run at many differenter center-of-mass energies

this leads to many detector requirements, which are best satisfied with more than one detector → we are aiming at 4 detectors in 4 interactions points with complementary strengths
Example of competing constraints for EM calorimeter: high E precision vs. high granularity vs. high stability vs. geometric accuracy vs. PID

- many measurements will serve as input to future programs in particular FCC-hh
- many are statistically limited
- redundancy provided by 4IPs/detectors is essential for high precision measurements (hidden systematic biases)

The limitation in maximum energy (not as strong for a linear collider) is not a crucial drawback, given the current HEP panorama given by the SM, and the subsequent FCC-hh program which will reach the highest energies

The non availability of beam polarization (an advantage of linear colliders) is also not a crucial drawback since FCC-ee will run at different energies and will accumulate much more statistics.
at Circular Colliders ➔ Rich e⁺e⁻ Physics Program ...

**EW & QCD**
- $m_Z$, $\Gamma_Z$, $N_e$
- $R_l$, $A_{FB}$
- $m_W$, $\Gamma_W$
- $\alpha_s(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

**detector hermeticity tracking, calorimetry**

**particle flow, energy resol., particle ID**

**direct searches of light new physics**
- Axion-like particles, dark photons, heavy neutral leptons
- Long lifetimes - LLPs

**flavour factory**
- $10^{12}$ bb/cc; $1.7 \times 10^{11}$ $\tau\tau$

**τ physics**
- $\tau$-based EWPOs
- Lept. univ. violation tests

**momentum resol. tracker**

**B physics**
- Flavour EWPOs ($R_b$, $A_{FB}^{b,c}$)
- CKM matrix
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., $b \rightarrow s\tau\tau$

**vertexing, tagging energy resolution hadron identification**

**"intensity frontier"**

**Higgs**
- $\tau$, $m_H$, $\Gamma_H$
- Higgs couplings self-coupling

**Top**
- $m_{top}$, $\Gamma_{top}$
- EW top couplings

**$\sqrt{s} = 240$, 365 GeV**
- $10^6$ HZ events
- $10^8$ WW $\rightarrow$ H events

**$\sqrt{s} = 340 \rightarrow 365$ GeV**
- $10^6$ tt events

Gregorio Bernardi APC - Paris
The potential of an hh machine at the energy frontier in the same circular tunnel is also excellent:

- Measurement of Higgs Self-coupling at the 3 to 4% level
- Highest reach in sensitivity for di-higgs studies, dark matter searches and more
- New heavy particles could be directly discovered for masses up to 20-40 TeV
- Large potential also from indirect searches
- Possibility for an eh and/or Heavy-ion program at the highest energies

But we are not ready to build the hh machine soon, more R&D on the magnets is needed, and reaching the high energy frontier with a Muon Collider could take even more time, if proven possible.

European Strategy recommendations in 2020

“Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV, with an electron-positron Higgs and electroweak factory as a possible first stage.”

“Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.”
Goal of the study:
Provide by 2025 conclusions on the technical and financial feasibility of the FCC-INT project, to be submitted/approved at the next European Strategy in 2026, eventually allowing to start digging the tunnel
The FCC integrated program (FCC-INT) at CERN is inspired by the successful LEP – LHC (1976-2041) program.

Comprehensive cost-effective program maximizing physics opportunities
- Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs, EW and top factory at highest luminosities.
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with heavy ions and eh options.

Complementary physics
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN’s existing infrastructure.

The FCC-INT project is fully integrated with HL-LHC exploitation and provides a natural transition for higher precision and energy.
FCC-ee run plan

Z factory: LEP $\times 10^5$
ILC $\times 10^3$

<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 $\pm$ 100 KeV</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 $&lt;$200 KeV</td>
<td>12</td>
<td>$10^8$ WW events</td>
</tr>
<tr>
<td>FCC-ee-H</td>
<td>3</td>
<td>240 $\pm$ 1 MeV</td>
<td>5</td>
<td>$10^6$ ZH events</td>
</tr>
<tr>
<td>FCC-ee-tt</td>
<td>5</td>
<td>345-365 $\pm$ 2 MeV</td>
<td>1.5</td>
<td>$10^6$ $t\bar{t}$ events</td>
</tr>
</tbody>
</table>

+ possible Run at the H pole (125 GeV) to access the Hee Yukawa coupling (never done, not doable anywhere else)
Detector requirements (present status)

"Higgs Factory" Programme
- Momentum resolution of $\sigma_{pT}/p_T^2 \approx 2 \times 10^{-5} \text{GeV}^2$ commensurate with $O(10^{-3})$ beam energy spread
- Jet energy resolution of 30% / $E$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for $c$, $b$ tagging

Ultra Precise EW Programme
- Absolute normalisation (luminosity) to $10^{-4}$
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to $10^{-5}$
- Momentum resolution "as good as we can get"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from $\mu\mu$)
- Stability of B-field to $10^{-6}$: stability of $\nu$s meat.

Heavy Flavour Programme
- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time meat.
- ECAL resolution at the few % / $E$ level for inv. mass of final states with $\pi^0$s or $\eta$s
- Excellent $\pi^0/\gamma$ separation and measurement for tau physics
- PID: $K/\pi$ separation over wide momentum range for $b$ and $\tau$ physics

Feebly Coupled Particles - LLPS
Benchmark signature: $Z \rightarrow \nu N$, with N decaying late
- Sensitivity to far detached vertices (mm $\rightarrow$ m)
  - Tracking: more layers, continuous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths $\Rightarrow$ extended detector volume
- Hermeticity

rare $H$ decays (e.g. $H \rightarrow \gamma + \phi/\psi/Y$ ) may benefit from high resolution EM calorimeter

lumi and $R_f$ require precision fiducial volume definitions (1-10 microns)
Detectors under Study

conceptually extended from the CLIC detector design
- full silicon tracker
- 2T magnetic field
- high granular silicon-tungsten ECAL
- high granular scintillator-steel HCAL
- instrumented steel-yoke with RPC for muon detection

explicitly designed for FCC-ee/CepC
- silicon vertex
- low $X_0$ drift chamber
- drift-chamber silicon wrapper
- MPGD/magnet coil/lead preshower
- dual-readout calorimeter: lead-scintillating cerenkov fibers

explicitly designed for FCC-ee,
recent concept, under development
- silicon vertex
- Low $X_0$ drift chamber
- Thin Solenoid before the Calorimeter
- High Granularity Liquid Argon Calorimetry

But several other options like Crystal Calorimetry (active in US, Italy), are under study
(similarly for tracking, muons and particle ID)

With potentially 4 experiments, many complementary options will be implemented
Physics of the Higgs boson at FCC-ee

Baseline (2IP): at 240 and 365 GeV, collect in total 1.2M ZH events and 0.1M WW→H events

• **Statistics-limited measurements:**
  - Higgs couplings to fermions & bosons
    → Model-independent measurements, normalized to $e^+e^- \rightarrow ZH$ cross-section
    → fixed candle ($H \rightarrow ZZ$) for past and future (FCC-hh) studies at hadron colliders
  - Higgs properties: CP violation, $H \rightarrow gg$, Higgs width, Higgs mass

• **Close to discovery level:**
  - Higgs self-coupling via loop diagrams:
    → complementarity to HH production at higher energy machines, like HL-LHC, or later FCC-hh

• **Unique possibility studied at FCC-ee:**
  - Measure Higgs to electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s} = 125$ GeV
    highly demanding on luminosity, monochromatization with 2 or 4 IPs?
    → test of first generation yukawa coupling
Measurement of the Higgs self-coupling

- assuming all other couplings at MS, $\Delta \kappa/\kappa \sim 19\%$ (12\% 4 I.P.)
- maximum sensitivity at the threshold production

50\% sensitivity: establish that $h^3 \neq 0$ at 95\% CL
20\% sensitivity: 5\sigma discovery of the SM $h^3$ coupling
5\% sensitivity: getting sensitive to quantum corrections to Higgs potential
The Tera-Z program at the Z peak and Electroweak Physics

The electroweak program at the Z peak and at the WW threshold is quite unique, most challenging, and could be the most promising part of the program given the statistics!

- \( L = 230/\text{cm}^2/\text{s} \) and 35 nb of Z cross section corresponds to 80 kHZ of events with typically 20 charged and 20 neutral particles (all to be fully recorded, stored, reconstructed)
- 3 years at \( 10^7 \) s/year = 2.4 \( 10^{12} \) evts/exp. \( \Rightarrow 10^5 \) LEP Statistics (~\( 10^3 \) more than ILC)

For the electroweak program we will also have
- 2 years at the WW threshold, \( 10^8 \) events/exp. \( \Rightarrow 2.10^3 \) LEP Statistics

Expected precisions in a nutshell:
- \( m_Z \): position of Z peak
- Beam energy measured with extraordinary precision (\( \Delta E/\Delta E < 100 \text{ keV} \)) using resonant depolarization of transversely polarized beams (method already used at LEP, much better prepared now, calibrations in situ with pilot bunches, no energy extrapolations, ...)
- Beam width/asymmetries studied analyzing the longitudinal boost distribution of the \( t\bar{t} \) system

With \( m_{t\bar{t}}, m_W \) and \( m_H \) fixed by measurements: the SM has nowhere to go!

Increased precision could show first hints of physics beyond the SM.
- Improve the direct determination of \( MW \) and \( M_{t\bar{t}} \)
- PDG 2020: \( MW \) to 12 MeV
- And the SM fit prediction for these quantities, e.g.:

\[
m_W = 80.3584 \pm 0.0055_{m_{t\bar{t}}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{\text{QED}}} \pm 0.0020_{\text{OS}} \pm 0.0001_{\text{Higgs}} \pm 0.0004_{\text{GEV}},
\]

\[
= 80.358 \pm 0.009\text{GEV},
\]

Requires improved measurements of \( m_{t\bar{t}}, m_Z, \alpha_{\text{QED}}(m_Z^2), \alpha_S ... \) and more generally all usual EWPO included in the EW fits.
### EW & QCD precision measurement examples

<table>
<thead>
<tr>
<th></th>
<th>stat</th>
<th>w/ syst (*)</th>
<th>improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_W$</td>
<td>400 keV</td>
<td>500 keV</td>
<td>30</td>
</tr>
<tr>
<td>$M_Z$</td>
<td>4 keV</td>
<td>&lt; 100 keV</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>$\Gamma_Z$</td>
<td>4 keV</td>
<td>&lt; 25 keV</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>$\sin^2\theta_{\text{eff}}$ (τ pol.)</td>
<td>$3 \times 10^{-6}$</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>$\alpha_{\text{QED}}(m_Z^2)$</td>
<td>$3 \times 10^{-5}$</td>
<td>$3 \times 10^{-5}$</td>
<td>4 (stat. lim. !)</td>
</tr>
<tr>
<td>Rb</td>
<td>$3 \times 10^{-7}$</td>
<td>$2 \times 10^{-5}$</td>
<td>30</td>
</tr>
<tr>
<td>$\alpha_{\text{S}}(m_{2Z})$</td>
<td>$10^{-5}$</td>
<td>$10^{-4}$</td>
<td>30</td>
</tr>
<tr>
<td>$M_{\text{top}}$</td>
<td>20 MeV</td>
<td>40 MeV</td>
<td>12</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Huge statistics: very small stat errors call for very small syst uncertainties too.
  - E.g. acceptances, should be known to 10-4 – 10-5
- Goal: $\sigma(\text{exp syst}) \approx \sigma(\text{stat})$
- Work on theo. side also critical (and initiated, 1809.01830)

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One key experimental handle: knowledge of $\sqrt{s}$ (exquisite at circular collider with resonant depolarisation method, at Z & WW)

In terms of weakly-coupled new physics: FCC-ee precision corresponds to sensitivity on $\Lambda_{NP}$ up to 70 TeV, anticipating what FCC-pp would focus on.
• Expect 1 M $t\bar{t}$ events, not so many compared to LHC, but in a clean environment and with the ability to scan $\sqrt{s}$

• Test of Higgs mechanism via measurement of top mass and top Yukawa coupling
  • $m_t$ measurement at FCC-ee with clear interpretation from cross section measurement near threshold
  • Simultaneous fit for $m_t$ and $\Gamma_t$ with statistical uncertainties of 17 MeV and 45 MeV respectively
  • Scale uncertainty of 45 MeV on $m_t$ from $N^3$LO QCD

• Extract $ttZ$ coupling from $\sigma(e^+e^- \rightarrow Z/\gamma^* \rightarrow t\bar{t})$
  → uncertainty ~10 times smaller than @HL-LHC
  → key input to extract top Yukawa coupling from FCC with reduced theory uncertainty
More on TeraZ: The Flavor/Tau Factory, QCD

Progress in flavour physics w.r.t. SuperKEKb / BELLE II requires > $10^{11}$ b pair events, FCC-ee(Z): will provide ~$10^{12}$ b pairs

<table>
<thead>
<tr>
<th>Particle production (10^9)</th>
<th>$B^0$</th>
<th>$B^-$</th>
<th>$B^0_s$</th>
<th>$\Lambda_b$</th>
<th>$c\bar{c}$</th>
<th>$\tau^-\tau^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle II</td>
<td>27.5</td>
<td>27.5</td>
<td>n/a</td>
<td>n/a</td>
<td>65</td>
<td>45</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>400</td>
<td>400</td>
<td>100</td>
<td>100</td>
<td>800</td>
<td>220</td>
</tr>
</tbody>
</table>

Precision of CKM matrix elements

<table>
<thead>
<tr>
<th>Observable / Experiments</th>
<th>Current W/A</th>
<th>Belle II (50/ab)</th>
<th>LHCb-U1 (23/fb)</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ (uncert., rad)</td>
<td>1.296±0.087</td>
<td>1.136 ± 0.026</td>
<td>1.136 ± 0.025</td>
<td>1.136 ± 0.004</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ (precision)</td>
<td>5.9%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

$\rightarrow$ Push forward searches for FCNC, CP violation and mixing
$\rightarrow$ Study rare penguin EW transitions such as $b \rightarrow s \tau^+\tau^-$, spectroscopy (produce b-baryons, $B_s$ …)
$\rightarrow$ Test lepton universality with $10^{11}$ $\tau$ decays (with $\tau$ lifetime, mass, BRs) at $10^{-5}$ level, LFV to $10^{-10}$
- all very important to constrain / (provide hints of) new BSM physics.
$\rightarrow$ need special detectors (PID) under study

3×$10^{12}$ hadronic Z decay also provide precious input for QCD studies

High-precision measurement of $\alpha_s(m_Z)$ with $R_\ell$ in Z and W decay, jet rates, $\tau$ decays
Large $\sqrt{s}$ lever-arm between 30 GeV and 360 GeV, fragmentation, baryon production …
$\rightarrow$ Testing running of $\alpha_s$ and measuring $\alpha_s$ to excellent precision
Searches for Feebly Interacting particles

- We need new physics to explain the Universe puzzles without interfering with SM radiative corrections ➔ Searches for new feeble interactions/particles
- Dark photons, Axion Like Particles (ALP’s), sterile neutrinos, are all *feebly coupled* to SM particles
- FCC-ee can be compared to the other machines for its sensitivity to right-handed (sterile) neutrinos

These limits are relevant for Neutrino, Dark sectors and High Energy Frontiers

- Significant extension reach for observing *heavy neutrino decays*
- Large potential improvement in the sensitivity to *mixing of neutrinos* to the dark sector, using EWPOs ($G_F$ vs $\sin^2\theta_W^{\text{eff}}$ and $m_Z$, $m_W$, tau decays) which extends sensitivity to $10^{-5}$ mixing, all the way to very high energies (500-1000 TeV) [arXiv:2011.04725]
Summary: FCC-ee discovery potential and Highlights

FCC-ee could explore, observe and discover:

- **Explore** the 10-100 TeV energy scale (and beyond) with Precision Measurements
  - 20-100 fold improved precision on many EW quantities (equivalent to factor 5-10 in mass)
  - \( m_Z, m_W, m_{\text{top}}, \sin^2 \vartheta_{\text{eff}}, R_b, \alpha_{\text{QED}}, \alpha_s, \) Higgs and top quark couplings,
  - and provide model independent Higgs measurements which can be propagated to LHC and FCC-hh

- **Observe** at the > 3\( \sigma \) level, the Higgs couplings to the 1st generation, the Higgs Self-coupling

- **Discover** a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
  - FCNC (\( Z \rightarrow \mu\tau, e\tau \)) in \( 5 \times 10^{12} \) \( Z \) decays and \( \tau \) BR in \( Z \rightarrow 10^{11} \tau \tau \)
  - + flavour physics (\( 10^{12} \) bb events) (\( B \rightarrow s \tau \tau \) etc..)

- **Discover** dark matter as «invisible decay» of H or Z (or in LHC loopholes)

- **Discover** very weakly coupled particle in the 5 to 100 GeV energy scale
  - such as: Right-Handed neutrinos, Dark Photons, ALPS, etc...

- Many other opportunities in e.g. QCD (\( \alpha_s @ 10^{-4} \), fragmentations, \( H \rightarrow gg \) etc....

➔ Not only a Higgs Factory! \( Z \), Heavy Flavour, QCD and top are also important for ‘discovery potential’

- More info at the FCC Physics in Cracow (1/2023): [https://indico.cern.ch/event/1066234/](https://indico.cern.ch/event/1066234/)
FCC main goals until 2025, Outlook

Overall goal:
• Perform all necessary steps and studies to enable a project decision by 2026/27, at the anticipated date for the next ESU, and a subsequent start of civil engineering construction by 2028/29.

This requires successful completion of the following four main activities:
• Develop and establish a governance model for project construction and operation
• Develop and establish a financing strategy, including in-kind contributions
• Prepare all required project preparatory and administrative processes with the host states
• Perform site investigations to enable Civil Engineering planning and to prepare its tendering.

In parallel development preparation of TDRs and physics/experiment studies:
• Machine designs and main technology R&D lines
• completion of first physics case studies in 2021-22 → detector requirements
• reach out to all ‘European and International Partners’
• Establish user communities, work towards proto experiment collaboration by 2025/26
• R&D/detector concept studies and physics potential:
  - Higgs (including self-coupling and 1st generation) - Precision EW, top, and QCD measurements
  - Heavy Flavor Physics and Tau physics - LLP’s detection and other BSM searches

FCC, thanks also to synergies and complementarities between ee and hh machines, offers the best approach to today’s physics landscape
FCC-ee can be constructed while accomplishing the HL-LHC program
Energy consumption and Carbon footprint: FCC vs. other projects

Our first responsibility (as particle physicists) is to do the maximum of science

- With the minimum energy consumption and the minimum environmental impact for our planet
  - Should become one of our top-level decision criteria for design, choice and optimization of a collider

All Higgs factories have a “similar” physics outcome (ESU’20 and Snowmass’21)

- Natural question: what is their energy consumption or carbon footprint for the same physics outcome?
  - Circular colliders have a much larger instantaneous luminosity and operate several detectors
  - FCC-ee is at CERN, where electricity is already almost carbon-free

![Energy consumption (per Higgs)](image1.png)

![Carbon footprint (per Higgs)](image2.png)

arXiv:2208.10486

Energy consumption / Higgs with 2IP
Circular ~ Linear / 5

(independently of the location or the starting time of the collider)

Carbon footprint / Higgs with 2IP
FCC-ee ~ CLIC / 5 ~ ILC / 50

(if operating today)
Double ring $e^+ e^-$ collider

Common footprint with FCC-hh, except around IPs

Asymmetric IR layout and optics to limit synchrotron radiation towards the detector

2 or 4 IPs, large horizontal crossing angle 30 mrad, crab-waist collision optics (layouts with 4 IPs under study now)

Synchrotron radiation power 50 MW/beam at all beam energies

Top-up injection scheme for high luminosity
Requires booster synchrotron in collider tunnel
Following extensive placement review, choice made

8-site baseline “PA31”

<table>
<thead>
<tr>
<th>Number of surface sites</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSS@IP (PA, PD, PG, PJ)</td>
<td>1400 m</td>
</tr>
<tr>
<td>LSS@TECH (PB, PF, PH, PL)</td>
<td>2143 m</td>
</tr>
<tr>
<td>Arc length</td>
<td>9.6 km</td>
</tr>
<tr>
<td>Sum of arc lengths</td>
<td>76.9 m</td>
</tr>
<tr>
<td>Total length</td>
<td>91.1 km</td>
</tr>
</tbody>
</table>

- 8 sites – less use of land, <40 ha instead of 62 ha
- Possibility for 4 experiment sites in FCC-ee
- All sites close to road infrastructure (< 5 km of new road constructions for all sites)
- Vicinity of several sites to 400 kV grid lines
- Good road connection of PD, PF, PG, PH suggest operation pole around Annecy/LAPP
- Exchanges with ~40 local communes in preparation

FCC: optimized placement and layout
<table>
<thead>
<tr>
<th>Physics, experiments and detectors</th>
<th>Accelerators</th>
<th>Techn. coordination techn. infrastructure</th>
<th>Host State processes and civil engineering</th>
<th>Organisation and financing models</th>
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<tbody>
<tr>
<td>P. Janot, C. Grojean</td>
<td>T. Raubenheimer, F. Zimmermann</td>
<td>K. Hanke</td>
<td>T. Watson (1 Nov. '21)</td>
<td>P. Collier (interim)</td>
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<tr>
<td>M. McCullough, F. Simon</td>
<td>ee design K. Oide, A. Chance</td>
<td>Electricity distribution J.-P. Burnet</td>
<td>administrative processes F. Eder, J. Gutleber</td>
<td>project organisation model NN</td>
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<tr>
<td>detector concepts</td>
<td>hh design M. Giovannozzi</td>
<td>cooling &amp; ventilation G. Peon</td>
<td>placement studies J. Gutleber, V. Mertens</td>
<td>financing model F. Sonnemann</td>
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<tr>
<td>M. Dam, F. Sefkow, P. Roloff</td>
<td>technology R&amp;D R. Losito</td>
<td>integration, installation, transport, logistics, JP Corso, C Colloca, C Prasse</td>
<td>environmental evaluation J. Gutleber</td>
<td>procurement strategy and rules NN</td>
</tr>
<tr>
<td>P. Azzi, E. Perez</td>
<td>ee injector P. Craievich, A. Grudiev</td>
<td>general safety, access, radiation protection, T. Otto</td>
<td>tunnel, subsurface design J. Osborne</td>
<td>in-kind contributions NN</td>
</tr>
<tr>
<td>G. Ganis, C. Helsens</td>
<td>ee MDI M. Boscolo, M. Sullivan</td>
<td>Computing, controls, communication, networks D. Duellmann</td>
<td>surface buildings design NN</td>
<td>operation model P. Collier &amp; J. Wenninger</td>
</tr>
<tr>
<td>ee energy calibration &amp; polarization (EPOL) J. Wenninger A. Blondel</td>
<td></td>
<td>geodesy &amp; survey H. Mainaud Durand, A. Wieser</td>
<td>surface sites layout and access NN</td>
<td></td>
</tr>
</tbody>
</table>

Cryogenics systems L.P. Delprat
Operation, maintenance, availability, reliability J. Nielsen
Increasing international collaboration as a prerequisite for success:

links with science, research & development and high-tech industry will be essential to further advance and prepare the implementation of FCC

FCC Feasibility Study: 58 fully-signed previous members, 17 new members, MoU renewal of remaining CDR participants in progress
### FCC-ee and FCC-INT cost estimates

<table>
<thead>
<tr>
<th>Domain</th>
<th>Cost in MCHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1 - Civil Engineering</td>
<td>5,400</td>
</tr>
<tr>
<td>Stage 1 - Technical Infrastructure</td>
<td>2,200</td>
</tr>
<tr>
<td>Stage 1 - FCC-ee Machine and Injector Complex</td>
<td>4,000</td>
</tr>
<tr>
<td>Stage 2 - Civil Engineering complement</td>
<td>600</td>
</tr>
<tr>
<td>Stage 2 - Technical Infrastructure adaptation</td>
<td>2,800</td>
</tr>
<tr>
<td>Stage 2 - FCC-hh Machine and Injector complex</td>
<td>13,600</td>
</tr>
<tr>
<td>TOTAL construction cost for integral FCC project</td>
<td><strong>28,600</strong></td>
</tr>
</tbody>
</table>

**Total construction cost FCC-ee (Z, W, H) amounts to 10.5 BCHF + 1.1 BCHF (tt)**

- Associated to a total project duration of ~20 years (2028 – 2048)

**Total construction cost for subsequent FCC-hh amounts to 17 BCHF.**

- Associated to a total project duration of ~25 years (2040 – 2065)
- (FCC-hh standalone would cost ~25 BCHF, so not building FCC-ee in a first stage would be a marginal saving)

Need for the tunnel a special contribution of about 5 BCH.
Indicative scenarios of future colliders

ILC
- Japan
- 2038 start physics
- ILC: 250 GeV, 2 ab⁻¹
- 500 GeV, 4 ab⁻¹
- 1 TeV, \(\approx 4-5.4\) ab⁻¹
- Original from ESG by UB
- Updated 25/7/22 by MN
- Old schedule, no updated dates yet

CEPC
- China
- 2035 start physics
- CePC: 90/160/240 GeV, 100/6/20 ab⁻¹
- SppC: 75-125 TeV, 10-20 ab⁻¹
- Old schedule, no updated dates yet

LHC
- CERN
- HL-LHC (14 TeV, 3 ab⁻¹)
- LHC (13.6 TeV, 450 fb⁻¹)
- Schedule valid if special contribution approved by ~2028

FCC
- FCC base: 250 GeV, 2 ab⁻¹
- FCC: 550 GeV, 4 ab⁻¹
- FCC ee: 90/160/250 GeV, 150/10/5 ab⁻¹
- FCC hc: 350-365 GeV, 1.7 ab⁻¹
- FCC hh: 100 TeV, \(\approx 30\) ab⁻¹

CCC
- USA
- 2040 start physics
- CCC: 250 GeV, 2 ab⁻¹
- 550 GeV, 4 ab⁻¹
- 2 TeV, \(\approx 4\) ab⁻¹

Muon Collider
- 2045 start physics
- Muon Collider: 3 TeV
- Stage 2: 10 TeV, \(\approx 10\) ab⁻¹

Note: Possibility of 125 GeV or 1 TeV at Stage 1

Schedule ‘valid’ (250 GeV) if funding now

→ Schedules seem very optimistic
Two solutions under study

- **CLD:** All silicon: pixel VTX + strips tracker
  - Inner: 3 (7) barrel (fwd) layers (1% $X_0$ each)
  - Outer: 3 (4) barrel (fwd) layers (1% $X_0$ each)
  - Separated by support tube @ $r = 675$ mm (2.5% $X_0$)

- **IDEA:** Extremely transparent Drift Chamber
  - GAS: 90% He – 10% iC$_4$H$_{10}$
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of $X_0$ at 90°
    - Tungsten wires dominant contribution
  - Full system includes Si VXT and Si “wrapper”
Calorimetry – Jet Energy Resolution

Energy coverage $\leq 180$ GeV: $22 \sqrt{s}$, $7\lambda$

Jet energy: $\frac{\delta E_{\text{jet}}}{E_{\text{jet}}} \approx 30\% / \sqrt{E}$ [GeV]

⇒ Mass reconstruction from jet pairs
Resolution important for control of (combinatorial) backgrounds in multi-jet final states
- Separation of HZ and WW fusion contribution to $\nu\nuH$
- $Hz \rightarrow 4$ jets, $t\bar{t}$ events (6 jets), etc.
- At $\delta E/E \approx 30\% / \sqrt{E}$ [GeV], detector resolution is comparable to natural widths of $W$ and $Z$ bosons

To reach jet energy resolutions of $\sim 3\%$, detectors employ
- highly granular calorimetry
- Particle Flow Analysis techniques

Technologies being pursued
a) CALICE like – extremely fine segmentation (ILC, CLIC, CLD)
   - ECAL: W/Si or W/scint+SiPM
   - HCAL: steel/scint+SiPM or steel/glass RPC
b) Parallel fiber dual readout calorimeter (IDEA)
   - Fine transverse segmentation; longitudinal inf. via timing
c) Noble Liquid (e.g. LAr) ECAL + CALICE-like HCAL
   - Fine segmentation, high stability, $\frac{\delta E_{\text{EM}}}{E_{\text{EM}}} \sim 6\%-9\%$
ILD as a group got started around 2008

ILD’s roots are linear colliders, ILC in particular

ILD’s main objective is to develop the best possible experiment for a Higgs/ Electroweak and beyond facility

Result of recent membership confirmation:
- 58 institutes confirmed ILD membership
- Around 10 institutes as guests members

ILD has a concept of the detector, well defined with technological options where

The main components of ILD have been validated and beam-tested.

A coherent System design has been developed.

A complete and detailed Geant4 model of ILD exists and is used

Particle Flow:

The central guiding principle for the design of ILD:
- Granularity
- Hermeticity

Low material inner region:
- Very thin Silicon
- Large volume TPC

Particle ID is important:
- PID in TPC
- Timing as additional handle

ILD is very interested to contribute to the studies of such detectors at linear and circular collider concepts, to develop the best possible experimental proposal for a future Higgs factory
Higgs with High Energy colliders: $\text{ILC}_{500-1000}$, $\text{CLIC}_{3000}$, FCC-INT

FCC-INT = FCC-ee + FCC-hh has the best expectations

<table>
<thead>
<tr>
<th>Collider</th>
<th>$\text{ILC}_{500}$</th>
<th>$\text{ILC}_{1000}$</th>
<th>CLIC</th>
<th>FCC-INT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{HZZ}$ (%)</td>
<td>0.24 / 0.23</td>
<td>0.24 / 0.23</td>
<td>0.39 / 0.39</td>
<td>0.17 / 0.16</td>
</tr>
<tr>
<td>$g_{HWW}$ (%)</td>
<td>0.31 / 0.29</td>
<td>0.26 / 0.24</td>
<td>0.38 / 0.38</td>
<td>0.20 / 0.19</td>
</tr>
<tr>
<td>$g_{Hbb}$ (%)</td>
<td>0.60 / 0.56</td>
<td>0.50 / 0.47</td>
<td>0.53 / 0.53</td>
<td>0.48 / 0.48</td>
</tr>
<tr>
<td>$g_{Hcc}$ (%)</td>
<td>1.3 / 1.2</td>
<td>0.91 / 0.90</td>
<td>1.4 / 1.4</td>
<td>0.96 / 0.96</td>
</tr>
<tr>
<td>$g_{Hgg}$ (%)</td>
<td>0.98 / 0.85</td>
<td>0.67 / 0.63</td>
<td>0.96 / 0.86</td>
<td>0.52 / 0.50</td>
</tr>
<tr>
<td>$g_{H\tau\tau}$ (%)</td>
<td>0.72 / 0.64</td>
<td>0.58 / 0.54</td>
<td>0.95 / 0.82</td>
<td>0.49 / 0.46</td>
</tr>
<tr>
<td>$g_{H\mu\mu}$ (%)</td>
<td>9.4 / 3.9</td>
<td>6.3 / 3.6</td>
<td>5.9 / 3.5</td>
<td>0.43 / 0.43</td>
</tr>
<tr>
<td>$g_{H\gamma\gamma}$ (%)</td>
<td>3.5 / 1.2</td>
<td>1.9 / 1.1</td>
<td>2.3 / 1.1</td>
<td>0.32 / 0.32</td>
</tr>
<tr>
<td>$g_{H\gamma\gamma}$ (%)</td>
<td>– / 10</td>
<td>– / 10</td>
<td>7. / 5.7</td>
<td>0.71 / 0.70</td>
</tr>
<tr>
<td>$g_{Htt}$ (%)</td>
<td>6.9 / 2.8</td>
<td>1.6 / 1.4</td>
<td>2.7 / 2.1</td>
<td>1.0 / 0.95</td>
</tr>
<tr>
<td>$g_{HHH}$ (%)</td>
<td>27.</td>
<td>10.</td>
<td>9.</td>
<td>$\pm 3.8^*$</td>
</tr>
<tr>
<td>$\Gamma_H$ (%)</td>
<td>1.1</td>
<td>1.0</td>
<td>1.6</td>
<td>0.91</td>
</tr>
<tr>
<td>BR_{inv} (%)</td>
<td>0.23</td>
<td>0.22</td>
<td>0.61</td>
<td>0.024</td>
</tr>
<tr>
<td>BR_{EXO} (%)</td>
<td>1.4</td>
<td>1.4</td>
<td>2.4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

$\text{FCC-hh} > 10^{10}$ H produced

+ FCC-ee measurement of $g_{HZZ}$

$\rightarrow g_{HHH}$, $g_{H\gamma\gamma}$, $g_{H\gamma\gamma}$, $g_{H\mu\mu}$, BR_{inv} at high precision

*arXiv:2004.03505
FCC as a Higgs factory:

Higgs-strahlung ($e^+e^-\rightarrow ZH$): event rate & Signal/Bkgd are optimal at $\sqrt{s} \sim 240$ GeV : $\sigma \sim 200$ fb

- $1.2 \times 10^6$ $e^+e^-\rightarrow ZH$ events with 5 ab$^{-1}$
- Target: (few) per-mil precision, statistics-limited.
- Complemented with $\sim 100k$ events at $\sqrt{s} = 350 – 365$ GeV (of which 30% are via the WW fusion channel)
  - useful for measuring self-coupling and $\Gamma_H$ precisely.

- The Higgs-strahlung process is an $s$-channel process $\rightarrow$ maximal just above the threshold of the process
- Vector Boson Fusion is a $t$-channel process which yields a cross section that grows logarithmically with the c-o-mass energy
- The Higgs boson is also produced in association with fermion pair for instance, a top quark pair.
Couplings Measurements Comparison across Machines

<table>
<thead>
<tr>
<th>Collider</th>
<th>HL-LHC</th>
<th>ILC_{250}</th>
<th>CLIC_{380}</th>
<th>LEP3_{240}</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>$\delta g_{HZZ}/g_{HZZ}$ (%)</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>$\delta g_{HWW}/g_{HWW}$ (%)</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>$\delta g_{Hbb}/g_{Hbb}$ (%)</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>$\delta g_{Hcc}/g_{Hcc}$ (%)</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>$\delta g_{Hgg}/g_{Hgg}$ (%)</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>$\delta g_{HTT}/g_{HTT}$ (%)</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>$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)</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>$\delta g_{HYY}/g_{HYY}$ (%)</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>$\delta g_{Htt}/g_{Htt}$ (%)</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>

LHC caveats:
- Measure only couplings ratios
- Many SM couplings cannot be seen at LHC (light quarks, charm, electrons)
- Couplings to gluons are measured through $gg\rightarrow H$ production cross section

HL-LHC will produce many more Higgs than FCC-ee, hence dominate precisions for $H\mu\mu$, $H\gamma\gamma$, $Htt$

The precisions on these FCC-ee couplings are given for 2 IP. They will improve by ~30% with 4IP
Yukawa coupling to electrons via s-channel $e^+e^- \to H$ production

First generation Yukawa coupling will not be accessible at HL-LHC, FCC-hh or any other $ee$ machine:

- Higgs decay to $e^+e^-$ is unobservable: $\text{BR}(H \to e^+e^-) \propto m_e^2 \approx 5 \cdot 10^{-9}$
- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu \to H) \approx 70$ pb. Tiny $\kappa_e$ Yukawa coupling $\Rightarrow$ Tiny $\sigma(ee \to H)$:

$$\sigma(e^+e^- \to H) = \frac{4\pi\Gamma_H^2 \text{Br}(H \to e^+e^-)}{(\hat{s} - M_H^2)^2 + \Gamma_H^2 M_H^2} = 1.64 \text{ fb (}m_H=125 \text{ GeV, } \Gamma_H=4.2 \text{ MeV)}$$

- Huge luminosities available at FCC-ee:

In theory, FCC-ee running at H pole-mass $L_{\text{int}} \approx 20$ ab$^{-1}$/yr would produce $O(30,000)$ H's

- IF we can control: (i) beam-energy spread, (ii) ISR, and (iii) huge backgrounds, then:
  - Electron Yukawa coupling measurable.
  - Higgs width measurable (threshold scan)?
  - Separation of possible nearly-degen. H's?

Most significant channel: $e^+e^- \to H \to gg \Rightarrow jj$ final state
Higgs measurements that are already studied at FCC-ee:
- $\sigma(ZH)$ and $m_H$ from Higgs recoil, $Z \to ll$
- Higgs couplings to $b$, $c$, $g$, $s$
- Higgs to invisible
- Higgs self-coupling from precise $\sigma(ZH)$ measurements at 240 and 365 GeV
- $ee \to H$ production in s-channel at 125 GeV
- $\sigma(ZH)$ in $Z \to qq$ (starting)

Higgs measurements which are not studied yet:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct reconstruction of $m_H$ in hadronic final states</td>
<td>jet angular resolution, kinematic fits, b-tag effi &amp; purity (Possible link with meas. of $\sigma(ZH)$ in $Z \to qq$)</td>
</tr>
<tr>
<td>$\Gamma(H)$</td>
<td>• Lepton ID efficiencies; jet clustering algorithms, jet directions, kinematic fits</td>
</tr>
<tr>
<td>• $H \to ZZ$</td>
<td>• Visible and missing mass resolutions [expression of interest, but many channels]</td>
</tr>
<tr>
<td>• $ZH(WW)$, $ZH(bb)$</td>
<td></td>
</tr>
<tr>
<td>• $\nu\nu H(bb)$</td>
<td></td>
</tr>
<tr>
<td>H$z\gamma$ coupling (production and decay)</td>
<td>photon identification, energy and angular scale</td>
</tr>
<tr>
<td>Rare decays: $H \to \gamma\gamma$ and $H \to \mu\mu$ (unlikely to do better than HL-LHC..)</td>
<td>Photon ID and resolution, track resolution</td>
</tr>
<tr>
<td>$H \to \tau\tau$ and CP studies</td>
<td>Tau reconstruction, Pi0 id</td>
</tr>
</tbody>
</table>
## Uncertainties in EWPO

<table>
<thead>
<tr>
<th>Observable</th>
<th>present value $\pm$ error</th>
<th>FCC-ee Stat.</th>
<th>Comment and leading exp. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z$ (keV)</td>
<td>$91186700 \pm 2200$</td>
<td>4</td>
<td>From $Z$ line shape scan</td>
</tr>
<tr>
<td>$\Gamma_Z$ (keV)</td>
<td>$2495200 \pm 2300$</td>
<td>4</td>
<td>From $Z$ line shape scan</td>
</tr>
<tr>
<td>$\sin^2\theta_W$ ($\times 10^6$)</td>
<td>$231480 \pm 160$</td>
<td>2</td>
<td>2.4 from $A_{FB}^Z$ at $Z$ peak</td>
</tr>
<tr>
<td>$1/\alpha_{QED}(m_Z^2)(\times 10^4)$</td>
<td>$128952 \pm 14$</td>
<td>3</td>
<td>small from $A_{FB}$ off peak</td>
</tr>
<tr>
<td>$R_Z^t$ ($\times 10^4$)</td>
<td>$20767 \pm 25$</td>
<td>0.06</td>
<td>0.2-1 ratio of hadrons to leptons</td>
</tr>
<tr>
<td>$\alpha_s(m_Z^2)$ ($\times 10^4$)</td>
<td>$1196 \pm 30$</td>
<td>0.1</td>
<td>0.4-1.6 from $R_Z^t$ above</td>
</tr>
<tr>
<td>$\sigma_{had}$ ($\times 10^3$) (nb)</td>
<td>$41541 \pm 37$</td>
<td>0.1</td>
<td>4 peak hadronic cross section</td>
</tr>
<tr>
<td>$N_c(\times 10^3)$</td>
<td>$2996 \pm 7$</td>
<td>0.005</td>
<td>1 $Z$ peak cross sections</td>
</tr>
<tr>
<td>$R_b$ ($\times 10^3$)</td>
<td>$216290 \pm 660$</td>
<td>0.3</td>
<td>$&lt; 60$ ratio of $b$ to hadrons</td>
</tr>
<tr>
<td>$\Delta_{FB}$, $0$ ($\times 10^4$)</td>
<td>$992 \pm 16$</td>
<td>0.02</td>
<td>1-3 $b$-quark asymmetry at $Z$ pole</td>
</tr>
<tr>
<td>$\Delta_{FB}^{pol}$ ($\times 10^4$)</td>
<td>$1498 \pm 49$</td>
<td>0.15</td>
<td>$&lt; 2$ $\tau$ polarization asymmetry</td>
</tr>
<tr>
<td>$\tau$ lifetime (fs)</td>
<td>$290.3 \pm 0.5$</td>
<td>0.001</td>
<td>0.04 radial alignment</td>
</tr>
<tr>
<td>$\tau$ mass (MeV)</td>
<td>$1776.86 \pm 0.12$</td>
<td>0.004</td>
<td>0.04 momentum scale</td>
</tr>
<tr>
<td>$\tau$ leptonic ($\mu\nu_{\tau}$) B.R. (%)</td>
<td>$17.38 \pm 0.04$</td>
<td>0.0001</td>
<td>0.003 $e/\mu$ hadron separation</td>
</tr>
<tr>
<td>$m_W$ (MeV)</td>
<td>$80350 \pm 15$</td>
<td>0.25</td>
<td>0.3 From WW threshold scan</td>
</tr>
<tr>
<td>$\Gamma_W$ (MeV)</td>
<td>$2085 \pm 42$</td>
<td>1.2</td>
<td>0.3 From WW threshold scan</td>
</tr>
<tr>
<td>$\alpha_s(m_Z^2)(\times 10^4)$</td>
<td>$1170 \pm 420$</td>
<td>3</td>
<td>small from $R_Z^t$</td>
</tr>
<tr>
<td>$N_c(\times 10^10)$</td>
<td>$2920 \pm 50$</td>
<td>0.8</td>
<td>small ratio of invis. to leptonic</td>
</tr>
<tr>
<td>$m_{top}$ (MeV/$c^2$)</td>
<td>$172740 \pm 500$</td>
<td>17</td>
<td>small From $t\bar{t}$ threshold scan</td>
</tr>
<tr>
<td>$\Gamma_{top}$ (MeV/$c^2$)</td>
<td>$1410 \pm 190$</td>
<td>45</td>
<td>small From $t\bar{t}$ threshold scan</td>
</tr>
<tr>
<td>$\lambda_{top}/\lambda_{top}^{EW}$</td>
<td>$1.2 \pm 0.3$</td>
<td>0.10</td>
<td>small From $t\bar{t}$ threshold scan</td>
</tr>
<tr>
<td>$t\bar{t}Z$ couplings</td>
<td>$\pm 30%$</td>
<td>$0.5 - 1.5$</td>
<td>small From $\sqrt{s} = 365$ GeV run</td>
</tr>
</tbody>
</table>

Systematics on the Electroweak Precision Observables in the table are preliminary and often largely dominant.

We use the statistical errors (after selection efficiencies and background subtractions) as the best way to assess the physics potential of a facility, since the systematic uncertainties get generally reduced making clever use of the statistics and additional theoretical calculations.

We are concentrating now on finding the potential ‘show stoppers’ or ‘stumbling blocks’, to guide the detector R&D and detector requirements.

Strong support for theoretical calculations will be needed if the program is to be successful.

Theory work is critical and initiated (1809.01830)
**FCC**

**EW measurements to be studied in detail:**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total width of the Z</td>
<td>scale (magnetic field) stability</td>
</tr>
<tr>
<td>Rb, Rc, (AFB)</td>
<td>Flavour tagging, acceptance, QCD corrections</td>
</tr>
<tr>
<td>Ratio Rl = Gamma_had / Gamma_l</td>
<td>Geometrical acceptance for lepton pairs</td>
</tr>
<tr>
<td>Tau polarisation</td>
<td>ECAL granularity</td>
</tr>
<tr>
<td>AFB (muons)</td>
<td>QED corrections</td>
</tr>
<tr>
<td>Luminosity from diphoton events</td>
<td>e/gamma separation, gamma acceptance</td>
</tr>
<tr>
<td>Coupling of Z to nu_e</td>
<td>Photon energy resolution, acceptance, track eff</td>
</tr>
<tr>
<td>σ(ee → WW) and MW (threshold scan; direct reco also above threshold)</td>
<td>√s determination, bckgd control; angles, kinem. fits</td>
</tr>
<tr>
<td>Vcb via W → cb</td>
<td>Flavour tagging</td>
</tr>
<tr>
<td>W leptonic BRs</td>
<td>Lepton ID, acceptance</td>
</tr>
<tr>
<td>Meas of √s via radiative return</td>
<td>lepton and jet angular resolutions, acceptance</td>
</tr>
<tr>
<td>Top properties from threshold scan</td>
<td>Jet reco, b-tagging, kine fits</td>
</tr>
<tr>
<td>EW couplings of the top</td>
<td>Jet reco, b-tagging, kine fits</td>
</tr>
</tbody>
</table>

9/14/22

Gregorio Bernardi APC - Paris
<table>
<thead>
<tr>
<th>Measurement</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP violation in Bs → ΦΦ</td>
<td>PID, vertex, track resolution</td>
</tr>
<tr>
<td>B0 → π0π0 (→ eeγ )</td>
<td>Low energy γ’s in jets (ECAL resolution and granularity)</td>
</tr>
<tr>
<td>Bs → ττ</td>
<td>Vertexing</td>
</tr>
<tr>
<td>Meas of γ from B+ → DK+</td>
<td>Ks reconstruction</td>
</tr>
<tr>
<td>τ → 3μ, τ → μγ</td>
<td>resolutions</td>
</tr>
<tr>
<td>τ lifetime</td>
<td>Alignment, scale of vertex detector,</td>
</tr>
<tr>
<td>τ BRs</td>
<td>Lepton ID, PID, e/πi separation</td>
</tr>
<tr>
<td>τ mass</td>
<td>Track reco &amp; resolution (in multi-track collimated environment)</td>
</tr>
<tr>
<td>Charm physics</td>
<td></td>
</tr>
<tr>
<td>Masses, spectroscopy, exotics…</td>
<td></td>
</tr>
<tr>
<td>EW parameters, exclusive modes (Vcb, etc)</td>
<td>Flavour tagging</td>
</tr>
</tbody>
</table>

Flavour physics measurements to be studied in detail
## Higgs @ (HL)-LHC

Credit: M. Kado ‘22

<table>
<thead>
<tr>
<th>ATLAS - CMS Run 1 combination</th>
<th>ATLAS Run 2</th>
<th>CMS Run 2</th>
<th>Current precision</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_Y$</td>
<td>13%</td>
<td>$1.04 \pm 0.06$</td>
<td>$1.10 \pm 0.08$</td>
<td>6%</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>11%</td>
<td>$1.05 \pm 0.06$</td>
<td>$1.02 \pm 0.08$</td>
<td>6%</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>11%</td>
<td>$0.99 \pm 0.06$</td>
<td>$1.04 \pm 0.07$</td>
<td>6%</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>14%</td>
<td>$0.95 \pm 0.07$</td>
<td>$0.92 \pm 0.08$</td>
<td>7%</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>30%</td>
<td>$0.94 \pm 0.11$</td>
<td>$1.01 \pm 0.11$</td>
<td>11%</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>26%</td>
<td>$0.89 \pm 0.11$</td>
<td>$0.99 \pm 0.16$</td>
<td>11%</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>15%</td>
<td>$0.93 \pm 0.07$</td>
<td>$0.92 \pm 0.08$</td>
<td>8%</td>
</tr>
<tr>
<td>$\kappa_\mu$</td>
<td>-</td>
<td>$1.06^{+0.25}_{-0.30}$</td>
<td>$1.12 \pm 0.21$</td>
<td>20%</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>-</td>
<td>$1.38^{+0.31}_{-0.36}$</td>
<td>$1.65 \pm 0.34$</td>
<td>30%</td>
</tr>
<tr>
<td>$B_{inv}$</td>
<td>&lt; 11%</td>
<td>&lt; 16%</td>
<td>11%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

Nature 607, 52-59 (2022)  
Nature 607, 60-68 (2022)

### ATLAS and CMS

**HL-LHC Projection**

<table>
<thead>
<tr>
<th>Uncertainty [%]</th>
<th>Tot</th>
<th>Stat</th>
<th>Exp</th>
<th>Th</th>
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</thead>
<tbody>
<tr>
<td>$\theta$</td>
<td>1.8</td>
<td>0.8</td>
<td>1.0</td>
<td>1.3</td>
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<tr>
<td>$\theta_{W}$</td>
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<td>0.6</td>
<td>1.3</td>
<td>1.3</td>
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<tr>
<td>$\theta_{Z}$</td>
<td>1.5</td>
<td>0.7</td>
<td>0.6</td>
<td>1.2</td>
</tr>
<tr>
<td>$\theta_{g}$</td>
<td>2.5</td>
<td>0.9</td>
<td>0.8</td>
<td>2.1</td>
</tr>
<tr>
<td>$\theta_{t}$</td>
<td>3.4</td>
<td>0.9</td>
<td>1.1</td>
<td>3.1</td>
</tr>
<tr>
<td>$\theta_{b}$</td>
<td>3.7</td>
<td>1.3</td>
<td>1.3</td>
<td>3.2</td>
</tr>
<tr>
<td>$\theta_{\tau}$</td>
<td>1.9</td>
<td>0.9</td>
<td>0.8</td>
<td>1.5</td>
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<tr>
<td>$\theta_{\mu}$</td>
<td>4.3</td>
<td>3.6</td>
<td>1.0</td>
<td>1.7</td>
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<tr>
<td>$\theta_{Z\gamma}$</td>
<td>9.8</td>
<td>7.2</td>
<td>1.7</td>
<td>6.4</td>
</tr>
</tbody>
</table>

**TH Uncertainties dominant**  
(assumed to be 1/2 of Run 2)