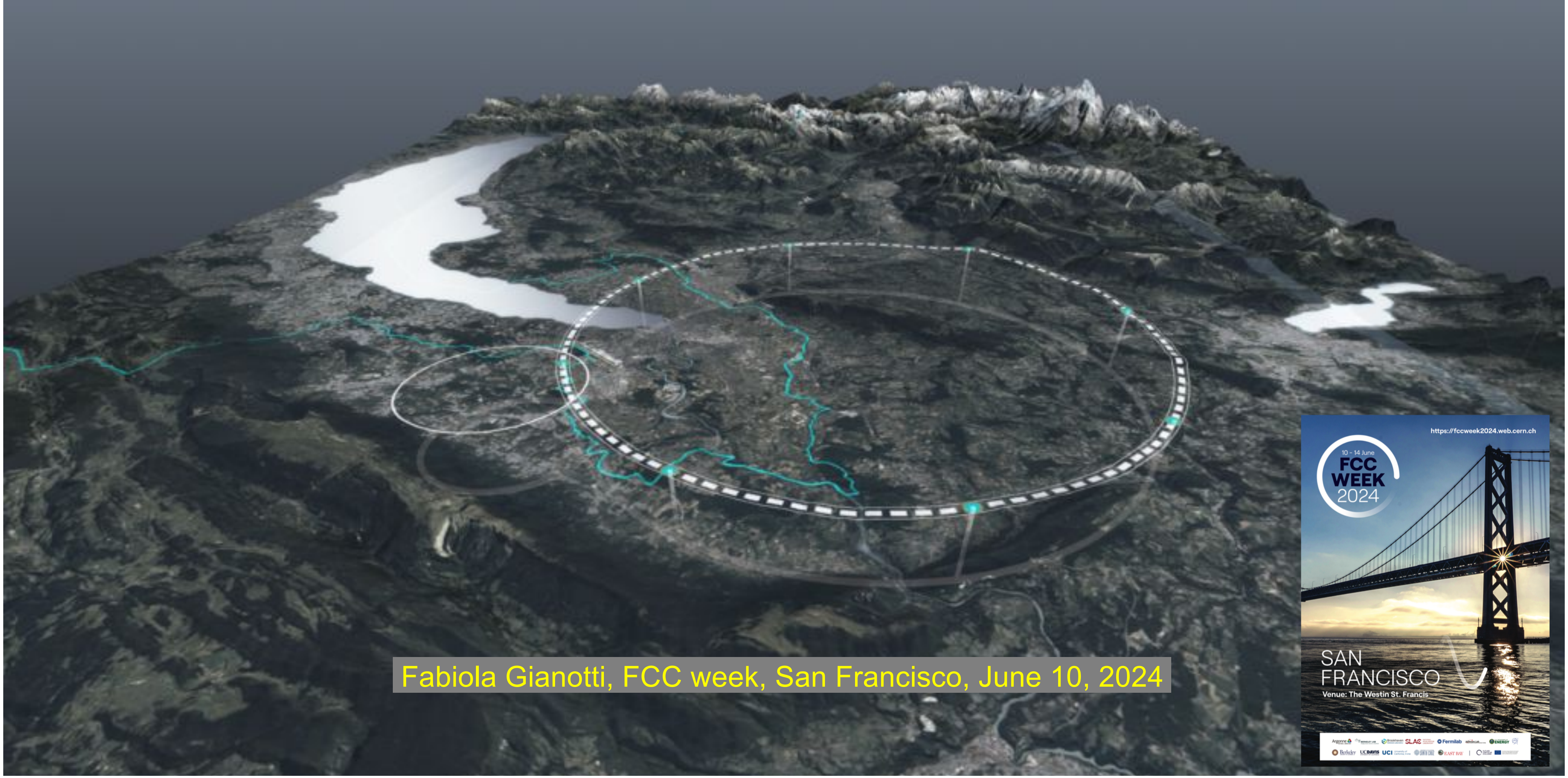
Future Circular Collider : CERN plans



Fabiola Gianotti, FCC week, San Francisco, June 10, 2024

Many thanks to

DOE and its national labs (SLAC, LBNL, ANL, BNL, FNAL, JLAB), as well as
UC Berkeley, UC Davis, UC Irvine, UC Santa Cruz, and California State University East Bay
for hosting us and their strong support

FCCIS: FCC Innovation Study (EC H2020 grant 951754)

FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

Industrial sponsors

Local Organizing Committee (chaired by Julia Gonski and Soren Prestemon)

Scientific Programme Committee

Michael Benedikt, Frank Zimmermann and CERN Organizing Committee

The FCC Collaboration

All of you for your participation and contribution!

Outlook

- ❑ CERN's scientific vision and current programme
- ❑ FCC motivations and main parameters
- ❑ FCC timeline and next steps
- ❑ Participation of the United States in FCC
- ❑ Conclusions

CERN’s scientific vision and current programme

Vision based on 3 pillars:

- ❑ a flagship project
- ❑ a diverse scientific programme complementary to the flagship project
- ❑ preparation of the future

CERN's current programme

- A "flagship" project. Currently operating and upgrading the world leading facility at the energy frontier: LHC and HL-LHC (until 2041)
  Note: LHC and HL-LHC are CERN's first priority. Success of the LHC programme is an essential prerequisite in view of a future collider

- A broad diverse scientific programme, complementary to the collider and carried out mainly at the injectors: continously upgraded and expanded. It currently includes also the Neutrino Platform, supporting the participation of Europe in compelling accelerator-based neutrino projects, mainly LBNF/DUNE in the US

- Currently preparing for the next major project, commensurate with the Lab's scientific ambition, expertise, community and infrastructure, to ensure a bright future for CERN and its community
  Preferred direction from 2020 European Strategy for Particle Physics (ESPP): FCC → Feasibility Study (FS) ongoing
  R&D and design studies for alternatives options (CLIC, muon colliders) also being pursued, as per the ESPP recommendation

- A vigorous and broad Accelerator R&D programme covering the technologies needed for the future of the field (superconducting high-field magnets, warm and superconducting accelerating structures, muon colliders, plasma wakefield, etc.).
  Carried out within the European Accelerator R&D Roadmap

- An ambitious Detector R&D programme to prepare the instruments needed for future projects.
  Carried out within the European Detector R&D Roadmap

- Computing developments to support the increasingly challenging requirements of the field (HL-LHC and beyond) and explore new technologies such as Quantum Computing and AI

- Inspiring and motivating research in theory, opening new avenues of exploration

CERN's scientific vision and current programme

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An exciting scientific programme for CERN's worldwide community made possible by:

- sustained funding from the Member and Associate Member States over the decades, and significant contributions from non-Member States (US in particular)
- an inclusive and diverse community of > 17,000 people from all over the world (> 110 nationalities)
- outstanding personnel expertise
- remarkable accelerator complex and other infrastructure and services, backed by a profound technology base

These assets, built over 70 years of history, provide a **strong foundation** for a future collider at CERN

- Computing developments to support the increasingly challenging requirements of the field (HL-LHC and beyond) and explore new technologies such as Quantum Computing and AI

- Inspiring and motivating research in theory, opening new avenues of exploration

FCC motivations and main parameters

Why FCC ?

1) Physics

Immense physics potential (best overall physics potential of all proposed future colliders)
A multi-stage facility at the energy and intensity frontier

- FCC-ee : highest luminosity at Z, W, ZH energies of all proposed Higgs and EW factories → ultra-precise measurements of Higgs boson and other EW parameters → indirect exploration of next energy scale (~ x10 LHC)
- FCC-hh : only machine able to explore next energy frontier directly (~ x10 LHC); unparalleled measurements of several Higgs couplings
- Also provides heavy-ion collisions and, possibly, ep/e-ion collisions
- 4 collision points → robustness; specialized experiments for maximum physics output

2) Timeline

- FCC-ee technology ~ mature → construction can proceed in parallel to HL-LHC operation and physics can start few years after end of HL-LHC operation (~ 2045) → This would allow ensure continuity of expertise and keep the community, in particular the young people, engaged and motivated.
- FCC-ee before FCC-hh would also allow:
  - cost of (more expensive) FCC-hh to be spread over more years
  - 20 years of R&D work towards affordable magnets providing the highest achievable field (HTS!)
  - optimization of overall investment: FCC-hh will reuse same civil engineering and large part of FCC-ee technical infrastructure

3) Community

It's the only facility commensurate to the size of the current CERN community (4 major experiments).
Note: for the future of the field, it's crucial to have facililites that expand (or at least maintain) the worldwide HEP community by offering a broad enough programme of exciting physics, experiments and technology, with the goal of attracting many new young talents

FCC-ee: summary of main machine parameters and physics potential

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr] 4 IPs	87	9.3	3.5	0.65
beam lifetime (rad Bhabha + BS+lattice)	8	18	6	10
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

Currently assessing technical feasibility of changing operation sequence (e.g. starting at ZH energy)

- x 10-50 improvements on all EW observables
- up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

FCC-hh: summary of main machine parameters for pp and physics potential

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 (Nb_3Sn) - 20 (HTS)	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity $[10^{11}]$	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity $[10^{34}\ cm^{-2}s^{-1}]$	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP $[fb^{-1}]$	20000	3000	300

If FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies (HTS) and lowest electricity consumption

Formidable challenges:
- high-field superconducting magnets: 14 - 20 T
- power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- stored beam energy: up to 9 GJ → machine protection
- pile-up in the detectors: ~1000 events/xing
- energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:
- Direct discovery potential up to ~ 40 TeV
- Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, μμ)
- Final word about WIMP dark matter
- Insight into EW phase transition in early universe

Development of many new, challenging technologies needed

Formidable technical challenges → vigorous R&D efforts in many areas required for both FCC-ee and FCC-hh

Emphasis also on sustainability and on minimising environmental impact

Examples of areas where vigorous R&D work is needed

High-field superconducting magnets with empahsis on HTS (for both FCC-hh and FCC-ee)

SRF cavities with increased gradient performance and energy efficiency

High-power RF sources (klystrons, solid state amplifiers) aiming at improving efficiency by up to 40% compared to current technology

New materials for collimators, masks and dumps, with low impedance and high thermal shock resistance

Surface treatment and coating techniques for vacuum components

Optimised cooling architectures to maxime waste heat reuse (including heat storage system)

New cryogenic fluids and thermodynamic processes to improve energy efficiency of cooling plants

Fertilisation of tunnel excavation material for agricultural use

Robotics and AI-based operation algorithms

Detector technologies coping with machine luminosities and radiation levels, and with performance matching expected stat. uncertainties

Note: huge potential applications to society: medicine, fusion, large tunnel infrastructures, electricity transmission, industry, etc.

FCC-ee cost and funding

FCC-ee construction cost up to operation at ZH : ~ 15 BCHF

Includes:
- ❑ Civil engineering (tunnel, experimental caverns, surface sites, etc.)
- ❑ FCC-ee collider and injectors
- ❑ Technical infrastructure
- ❑ Other infrastructure (roads, power lines, land, etc.)
- ❑ 4 detectors

Does not include upgrade to ttbar operation (~ 1.5 BCHF)

Updated cost assessment made in 2023, reviewed by dedicated Cost Review Panel of experts (chair N. Holtkamp), which concluded:
- ❑ cost estimates are appropriate for this stage of the study
- ❑ uncertainty estimates are realistic; most items are class 4 (- 30% to + 50%) or class 3 (-20% to +30%).
  Aim at class 3 for all main items at the end of the Feasibility Study

Note: **care should be taken when comparing with other proposed future colliders, whose cost estimates are in most cases not so detailed and complete, and have not been re-assessed recently** (high inflation over past years!)

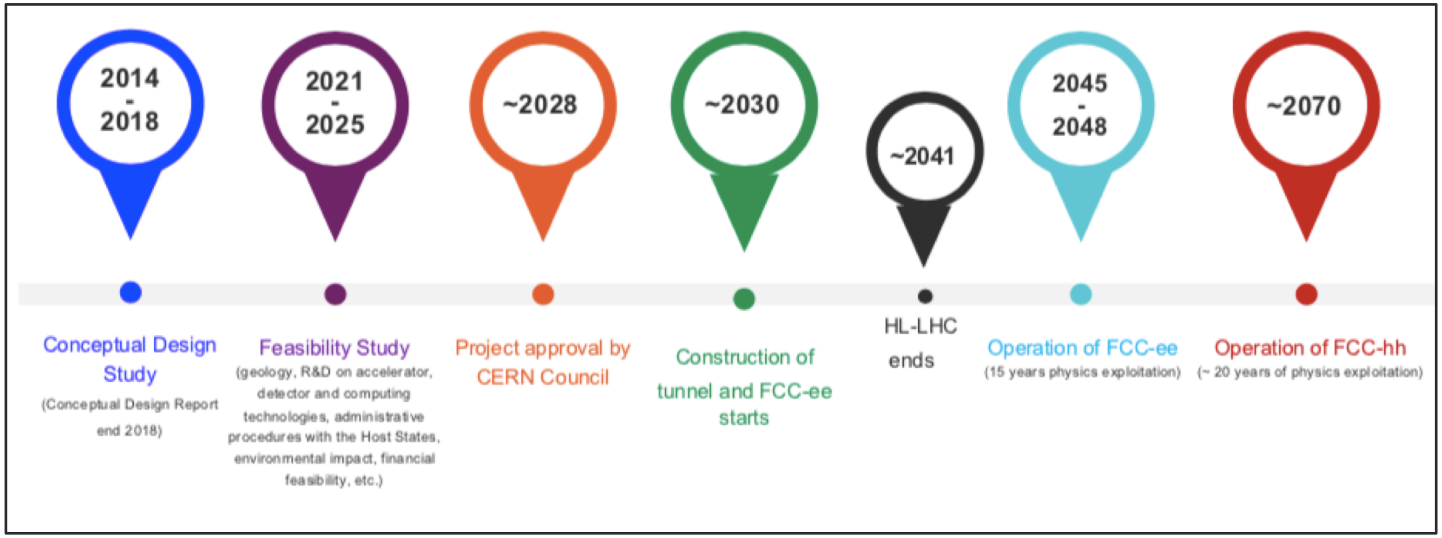
Funding

CERN Budget can cover more than half of the cost. Contributions expected from non-Member States with interested communities (e.g. US) and from Member States (beyond their contributions to CERN Budget).
Other contributions may come from the European Commission and private donors.

Preliminary funding model (including construction and operation expenses) and funding scenarios studied
→ will be further developed in the coming year based on discussions in Council and with potential partners.

FCC timeline and next steps

FCC timeline



1st stage collider FCC-ee:
electron-positron collisions 90-360 GeV: electroweak and Higgs factory
2nd stage collider FCC-hh:
proton-proton collisions at ~ 100 TeV

"Realistic" schedule taking into account:

- past experience in building colliders at CERN
- the various steps of approval process: ESPP update, CERN Council decision
- HL-LHC will run until ~ 2041

→ ANY future collider at CERN cannot start physics operation before ~ 2045 (but construction will proceed in parallel to HL-LHC operation)

Care should be taken when comparing to other proposed facilities, for which in most cases only the (optimistic) technical schedule is shown. In particular, studies related to **territorial implementation** (surface sites, roads, connection to water and electricty, environmental impact, admin procedures, etc.), which for FCC are being carried out in the framework of the Feasibility Studies, **take years.**

FCC Feasibility Study

From the 2020 update of the European Strategy for particle physics

"An electron-positron Higgs factory is the highest-priority next collider."

"For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."

"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 and 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."

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FCC Feasibility Study started in 2021:

- ❑ will be completed in March 2025 with Feasibility Study Report
- ❑ mid-term review to assess progress completed in Feb 2024
- ❑ covers the "integrated programme": FCC-ee followed by FCC-hh

  Reasons: 1) physics, 2) timeline (cost, maturity of technology), 3) overall investment (use of common tunnel and other infrastructure by both machines)

FCC Feasibility Study mid-term review

The goal of the FCC FS mid-term review was to assess the progress of the Study towards the final report

Deliverables (approved by Council in Sept 2022):
D1 : Definition of the baseline scenario
D2 : Civil engineering
D3 : Processes and implementation studies with the Host States
D4 : Technical infrastructure
D5 : FCC-ee accelerator
D6: FCC-hh accelerator
D7: Project cost and financial feasibility
D8: Physics, experiments and detectors

FS scope is actually much broader than just the project feasibility

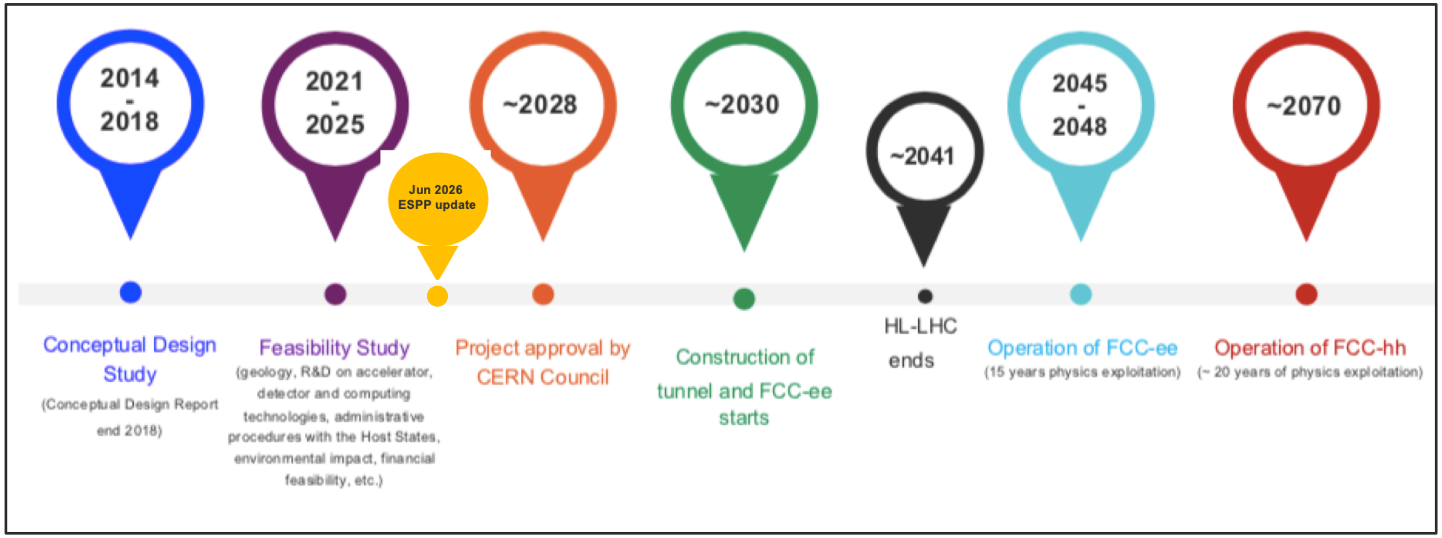
Documents:
- Mid-term report (all deliverables except D7; ~ 700 pages)
- Executive Summary of mid-term report (~ 50 pages)
- Updated cost assessment (D7)
- Funding model (D7)

Conclusion
- Extremely positive feedback from all committees
- Mid-term deliverables and goals met
- No technical show-stopper found at this stage.
- "The Council … congratulated and thanked all the teams involved in the Study for the excellent and significant work done so far and for the impressive progress, and looks forward to receiving the final report in 2025."

Review steps:
- Oct 2023: FCC FS Scientific Advisory Committee (scientific and technical aspects) and Cost Review Panel (ad hoc committee; cost and financial aspects)
- Nov 2023: CERN Scientific Policy Committee (SPC) and Finance Committee
- 2 Feb 2024: Council

Many thanks to all of them!

FCC timeline: next steps



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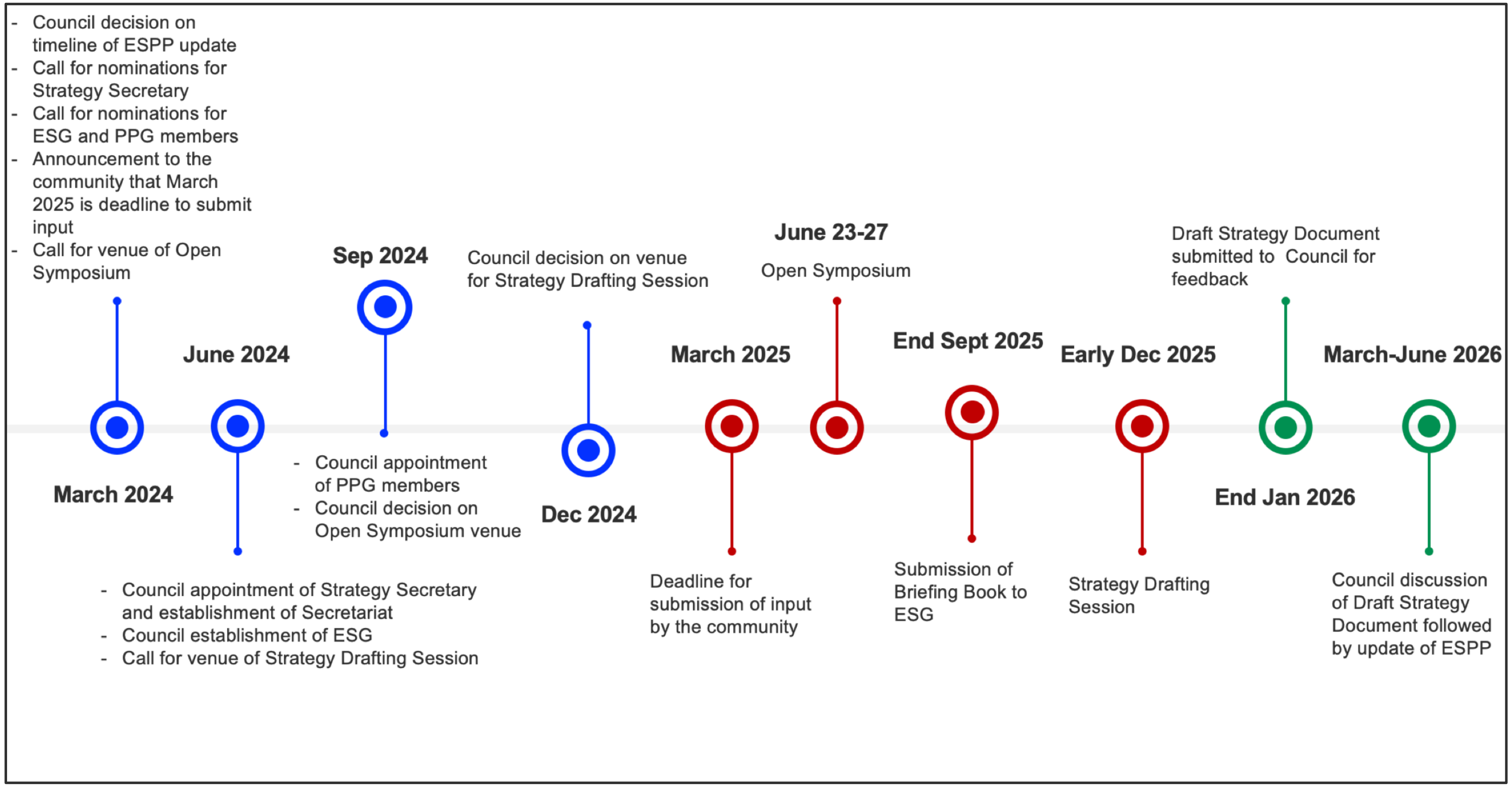
Next steps:
- ❑ Complete Feasibility Study by March 2025
- ❑ ESPP update: process started by Council in March → to be completed in June 2026 → see next slide
- ❑ Preparation for Council decision on FCC end 2027/beg 2028: “pre-TDR phase”

Timeline of European Strategy update

- Next week: appointment of Strategy Secretary, Strategy Secretariat and European Strategy Group (ESG) by CERN Council
- March 2025: deadline for submission of community input
- June 23-27, 2025: Open Symposium
- Early Dec 2025: Strategy Drafting Session
- June 2026: Strategy update by CERN Council → end of the process



Preparing for next step: pre-TDR phase (April 2025 - end 2027)

Main goal of Feasibility Study is to determine if there are any showstoppers for the implementation of the FCC.

More detailed technical studies and documentation are needed to allow the Council to take a decision, possibly at end 2027/beg 2028, on whether or not the project should go ahead

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The pre-TDR phase (April 2025 - end 2027) should prepare the needed input for a decision (note: construction start requires a full TDR)

Main goal of "pre-TDR" phase would be to further develop civil engineering and technical components and their integration, so as to provide a more detailed cost estimate with reduced uncertainties:

-- R&D and design studies of all main components of accelerators and technical infrastructure
-- full project integration study, including detector requirements
-- proto-collaborations around detector conceptual design activities

Another crucial goal of the pre-TDR phase would be to start a deeper environmental impact study (quantitative analysis of impact of FCC-ee components and mitigation measures)

The Council will consider the pre-TDR phase based on the final report of the FCC Feasibility Study; in the meantime, allocation of the necessary resources until that time will be considered for approval by Council next week.

Participation of the United States in FCC

FCC and the United States

- US scientists participating in FCC since initial Conceptual Design Study (2014)
- US-CERN Agreement for US participation in FCC FS signed Dec 2020 (Add. 3 to Protocol 3 of International Cooperation Agreement)
- US scientists involved in physics and detector studies, accelerator design and technologies for FCC-ee and FCC-hh, civil engineering
  Several of them are at the top level of the FCC Feasibility Study international organisation (→ see spare slide)
- Further US involvement essential → plenty of opportunities for important work and key roles (new detector concepts, advanced accelerator technologies, environmental impact and sustainability, etc.)

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Joint Statement of Intent between The United States of America and The European Organization for Nuclear Research concerning Future Planning for Large Research Infrastructure Facilities, Advanced Scientific Computing, and Open Science
Signed at the OSTP, DC on April 26, 2024

https://www.state.gov/joint-statement-of-intent-between-the-united-states-of-america-and-the-european-organization-for-nuclear-research-concerning-future-planning-for-large-research-infrastructure-facilities-advanced-scie/

"The US and CERN intend to continue to collaborate in the feasibility study of the Future Circular Collider Higgs Factory (FCC-ee), the proposed major research facility planned to be hosted in Europe by CERN with international participation, with the intent of strengthening the global scientific enterprise and providing a clear pathway for future activities in open and trusted research environments"

"Should the CERN Member States determine the FCC-ee is likely to be CERN's next world-leading research facility following the high-luminosity Large Hadron Collider, the United States intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals."

The FCC will not happen without the US participation in a leading role

Conclusions

FCC is scientifically the most compelling of all proposed future colliders and the one with the broadest physics programme
In the same tunnel and with the same technical infrastructure: e+e-, pp, heavy-ion collisions; potentially also e-p, e-ion
→ 2020 ESPP recommended it for feasibility study

It's also a big, audacious project, but so were LEP, Tevatron, LHC when they were first conceived.
They were successfully built, and performed beyond expectation → demonstration of capability of HEP community to deliver on very ambitious projects

Cost and funding are major challenges (as for any future collider) → crucial to work with all stakeholders (including new ones for HEP) to make it happen. The strong interest of and "pressure" from the community will be absolutely crucial.

Mid-term review of Feasibility Study successfully completed in Feb 2024 → no technical showstopper identified

Next steps:
- ❑ Feasibility Study final report to be completed March 2025
- ❑ Next update of the European Strategy June 2026
- ❑ Council decision on next project hopefully end 2027 or beg 2028

The FCC will not happen without the US participation in a leading role

Particle physics underpins our understanding of how the Universe has evolved from the first moments after the Big Bang right up until today. It underpins our understanding of the building blocks that make up the stars, planets, galaxies and life on Earth. And it underpins our understanding of the forces that hold everything together.

Over the years, we have learned that physics at the cosmological scales is intimately connected with physics at ultra-short distances (elementary particles).

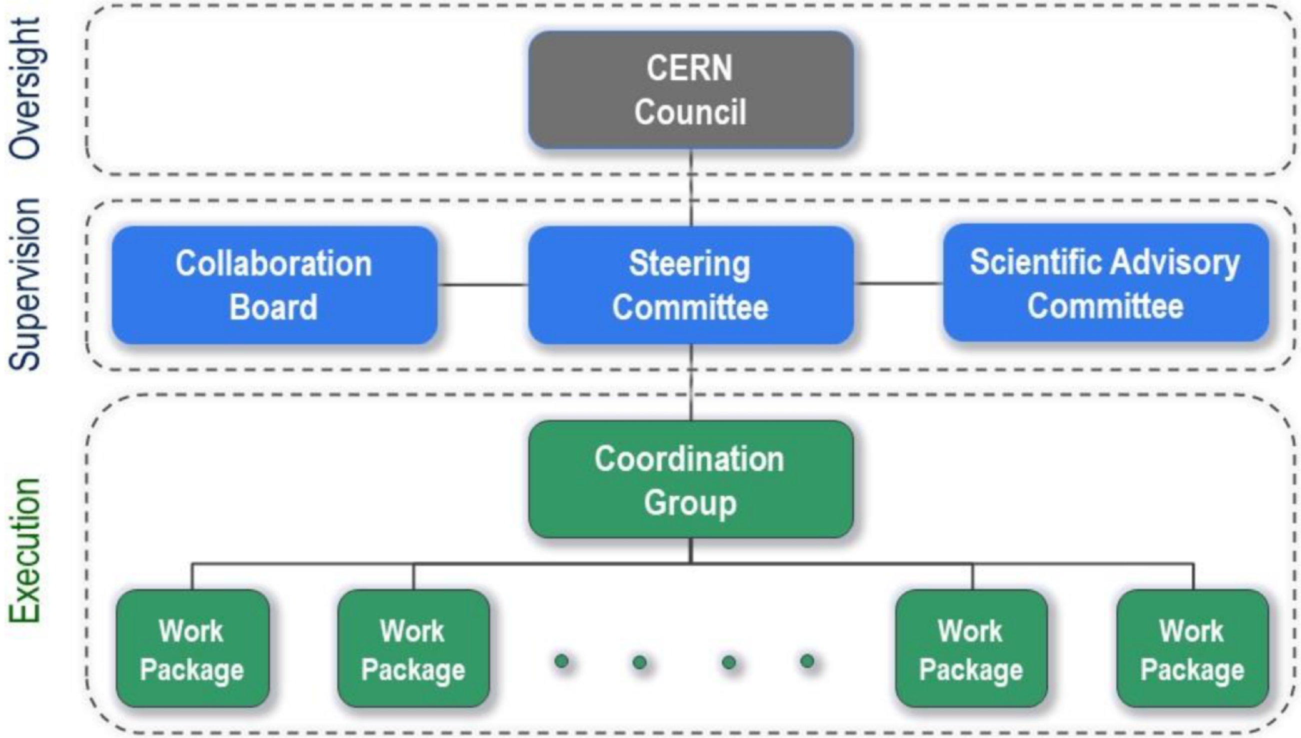
The discovery of the Higgs boson at CERN's Large Hadron Collider in 2012 was a momentous event. The Higgs boson is both the simplest and the most perplexing particle ever discovered. It is related to the mechanism that allowed matter to form in the early Universe, some 13.8 billion years ago, and thus enables us to exist. It may also be connected to the ultimate fate of the Universe. And it may play a role in explaining unanswered questions, such as the composition of dark matter, the disappearance of antimatter and the energy content of the Universe.

These and other mysteries show that we are missing something big in our understanding of the laws of nature and point to the need for a new, possibly revolutionary paradigm in fundamental physics. Discovering this new paradigm will require unprecedented tools of exploration and unprecedented technologies.

The Future Circular Collider will be the most extraordinary instrument ever built to study the fundamental laws of nature at the smallest distances, to nail down the characteristics of the Higgs boson and fully understand its role in the birth and the fate of the Universe, and to address the deep questions that connect the quantum world to the cosmological scales.

EXTRAs

FCC Feasibility Study 2021-2025: organisation



Lia Merminga (FNAL) is member of Steering Committee
Andy Lankford (UC Irvine) is vice-chair of Collaboration Board
Tor Raubenheimer (SLAC) co-convener of the Accelerators Work Package and member of Coordination group
Michiko Minty (BNL) is member of Scientific Advisory Committee
Norbert Holtkamp (Hoover Institution, Stanford University) and Jim Yeck (BNL) are Chair and member of the Cost Review Panel, respectively

ESPP committees for 2026 ESPP update

Strategy Secretariat
Assists the ESG by organising and running the ESPP process
Strategy Secretary (Chair), SPC Chair, ECFA Chair, LDG Chair

Physics Preparatory Group (PPG)
Collects community's input, organises Open Symposium, prepares Briefing Book
Strategy Secretariat (Strategy Secretary is Chair of PPG)
4 members appointed by Council on recommendation of SPC
4 members appointed by Council on recommendation of ECFA
1 representative appointed by CERN
2 representatives from Americas and 2 from Asia (appointed by respective ICFA representatives)

European Strategy Group (ESG)
Prepares the (Draft) Strategy Document
Strategy Secretariat (Strategy Secretary is Chair of ESG)
1 representative appointed by each Member State
1 representative appointed by each LDG laboratory
CERN DG + DG elect
Invitees: PPG, President of Council, 1 representative from each Associate Member State and Observer State,
1 representative from EC; chairs of ApPEC, NuPECC, ESFRI

Note: Council appoints the Strategy Secretary, and 8 members of PPG (4 on recommendation of SPC and 4 on recommendation of ECFA).
All other members are either ex-officio or are appointed by other entities (countries, EC, ICFA, etc.)

FUTURE CIRCULAR COLLIDER

Cost Classification

Cost Estimate Classification	Primary Characteristics		Secondary Characteristic	
	Level of Definition (% of Complete Definition)	Typical Estimating Technique of the Cost	Typical purpose of estimate	Expected accuracy range - Variation in low and high ranges
Class 5, Concept Screening	0% to 2%	Capacity factored, Stochastic, most Parametric models, judgement or analogy	Concept screening	L: -20% to -50% H: +30% to +100%
Class 4, Study or Feasibility	1% to 15%	Equipment factored, more Parametric models	Study or feasibility	L: -15% to -30% H: +20% to +50%
Class 3, Preliminary, Budget Authorization	10% to 40%	Semi-detailed unit costs with assembly level line items, cost estimating technique includes the combinations of various techniques (detailed, unit-cost, or activity-based; parametric; specific analogy; expert opinion; trend analysis)	Budget authorization or control	L: -10% to -20% H: +10% to +30%
Class 2, Control or Bid/Tender	30% to 70%	Detailed unit cost, cost estimating technique includes the combinations of various techniques (detailed, unit-cost, or activity-based; expert opinion; learning curve)	Control or bid/tender	L: -5% to -15% H: +5% to +20%
Class 1, Check Estimate or Bid/Tender	50% to 100%	Deterministic, most definitive cost estimation	Check estimate or bid/tender	L: -3% to -10% H: +3% to +15%

Class 4 or better for mid-term review

Class 3 for Feasibility Study report in 2025

Class 2-3 for pre-TDR phase in 2027

Association for the Advancement of Cost Engineering (AACE)