CERN vision and plans

Fabiola Gianotti (CERN)
P5 @ BNL, 13 April 2023

Initial remarks

CERN and US-HEP: a very strong, mutually-beneficial partnership over more than 40 years

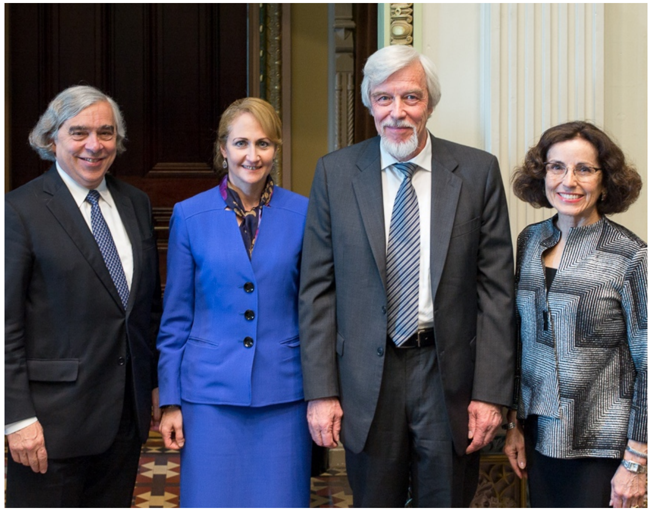
Today: US scientists are the single largest community of all CERN's users (~16% of CERN's users).
They represent ~50% of the US-HEP community.

The contributions of DOE, NSF and US scientists have been essential for the success of CERN's programme, in particular the LHC and now the accelerator and experiments upgrades for High-Luminosity LHC.

They will continue to be crucial also in the future. In particular, a Future Circular Collider (and/or any other future facility at CERN) will only be possible with the strong participation of US-HEP (people, ideas, technologies, resources).

Likewise, CERN is committed to the success of LBNF/DUNE and other ongoing collaborations with the US and ready to discuss cooperation on other future projects in the US (EIC, …).

The destinies of US-HEP and CERN are closely coupled



DOE-NSF-CERN International Cooperation Agreement signed in Washington D.C. on 7 May 2015. Figure shows Ernest Moniz (Secretary of Energy, DOE), Jo Handelsman (Associate Director of the White House Office of Science and Technology Policy), Rolf Heuer (DG, CERN), France Córdova (Director, NSF).

CERN in a few numbers

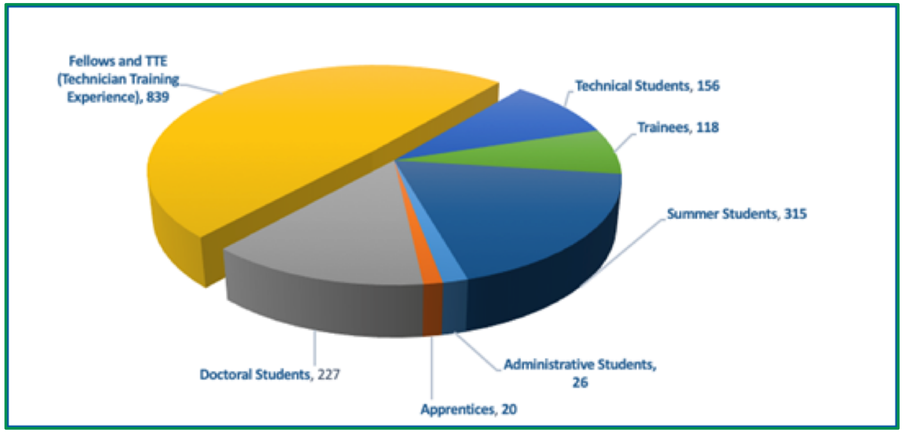
Funded in 1954; treaty-based intergovernmental organisation
23 Member States, 10 Associate Member States, 4 Observers (including US)
~ 50 International Cooperation Agreements with non-Member States

> 70 running experiments/facilities
Publications (2022): > 800 papers (experiments + theory, ~ 300 from LHC)

Annual Budget: 1.3 BCHF
(shared by Member States based on their net national income)

CERN's community: > 16900 people (> 110 nationalities)

- 2658 staff
- 900 fellows (post-docs)
- 11860 users (number doubled with advent of LHC), 1516 other associates
- 3504 PhD students from all over the world
- ~ 4500 young people trained at CERN at any time
- US population: 1902 users from 142 Institutes



2 main sites in CH and France, 15 smaller satellite sites
630 hectares, 700 buildings
70 km underground tunnels, > 30 caverns
1000 km technical galleries/trenches
500 hotel rooms
3000 meals served daily
4000 contractors' personnel
9000 people on site every day

Every year:
150000 visitors to CERN
170000 press cuttings
5 million visitors to CERN website
130 million CERN social media views

CERN's scientific vision and programme: 3 pillars

Based on European Strategy for Particle Physics (ESPP): latest update in 2020

Full exploitation of the LHC:

- successful Run 3: $\sqrt{s}$ =13.6 TeV
- High-Luminosity LHC upgrade (construction underway) → starts in 2029 ends in 2041 (goal is 3000 fb^{-1} to ATLAS and CMS)

"Scientific diversity" programme complementary to LHC experiments:

- current experiments and facilities at Booster, PS, SPS and their upgrades (recently AD/ELENA and East Area)
- participation in accelerator-based neutrino projects outside Europe (presently mainly LBNF/DUNE) through Neutrino Platform
- short/medium-term future opportunities discussed within "Physics Beyond Colliders" study group

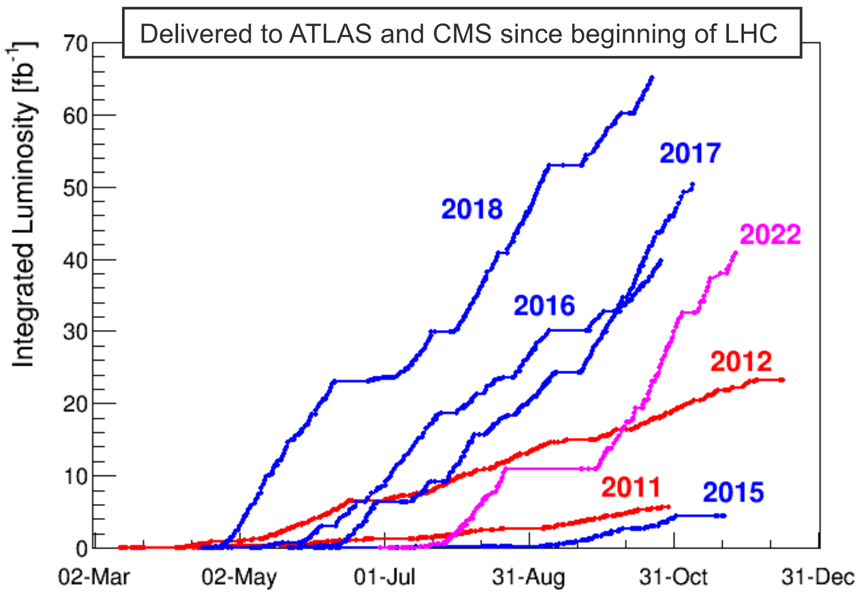
Preparation of CERN's future:

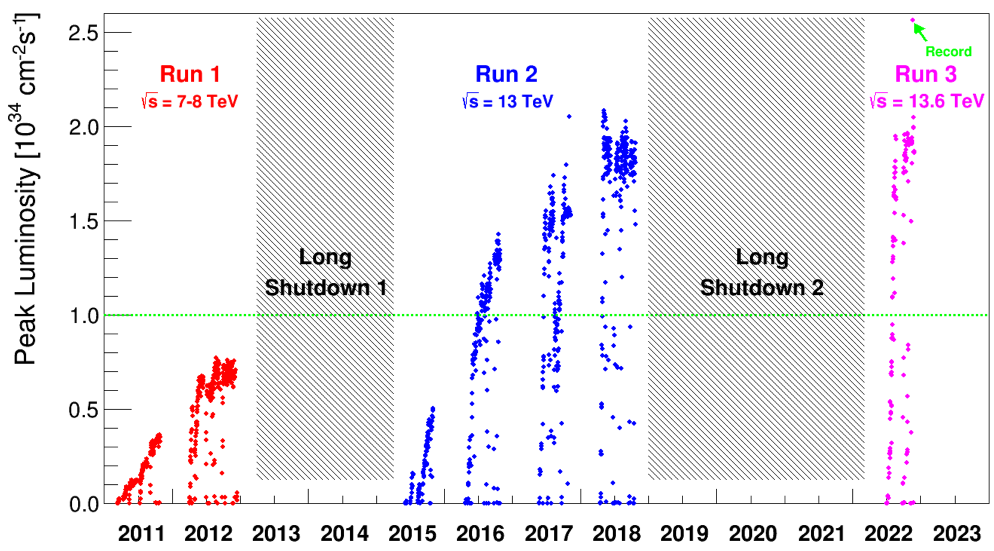
- intense accelerator, detector and computing R&D programmes
- Future Circular Collider (FCC) Feasibility Study → final report end 2025
- R&D and design studies for alternative options: CLIC, muon colliders → reports end 2025

ESPP next update expected around 2026-2027 → input to be submitted by end 2025

LHC and HL-LHC

LHC : a success story





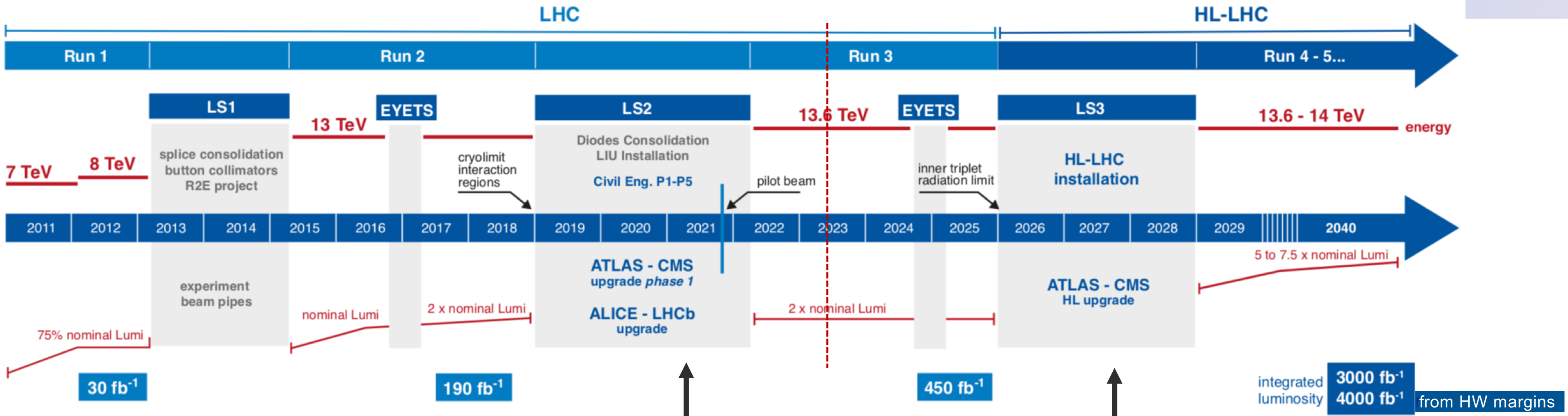
Achieved max peak luminosity: ~2.6×10^{34} cm^{-2} s^{-1} (x2.6 design value)

Run 1 (2010-2012) delivered: ~ 30 fb^{-1} at $\sqrt{s}$ = 7-8 TeV
Run 2 (2015-2018) delivered: ~ 160 fb^{-1} at $\sqrt{s}$ = 13 TeV
Run 3 (2022-2025) delivered so far (2022): ~ 40 fb^{-1} at $\sqrt{s}$ = 13.6 TeV (target was 25 fb^{-1})
Integrated luminosity delivered to ATLAS and CMS so far (230 fb^{-1}) is only 7.5% of total luminosity expected at end of HL-LHC
Luminosity targets for Run 3: 260 fb^{-1} ATLAS and CMS, 25-30 fb^{-1} LHCb, 7 nb^{-1} Pb-Pb ALICE

Total expected LHC luminosity (Run 1+ Run 2 + Run 3): > 450 fb^{-1} to ATLAS and CMS (design target was 300 fb^{-1})

> 3300 publications in peer-reviewed journals since beginning of LHC in 2009

High-Luminosity LHC (HL-LHC)



LS2
LHC Injectors Upgrade (LIU) completed
Phase-1 upgrades: major for LHCb and ALICE

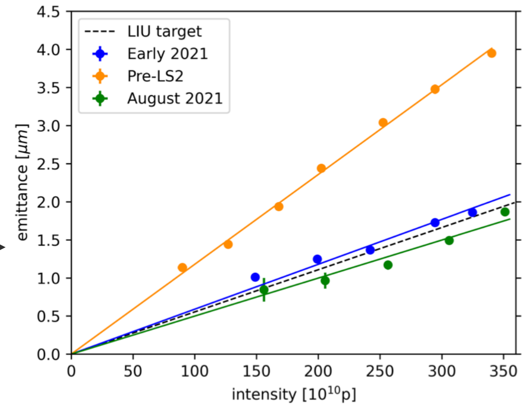
LS3
Installation of HL-LHC machine upgrades
Phase-2 upgrades of ATLAS and CMS

LHCb and ALICE plan major upgrades in LS4 (2033-2034)

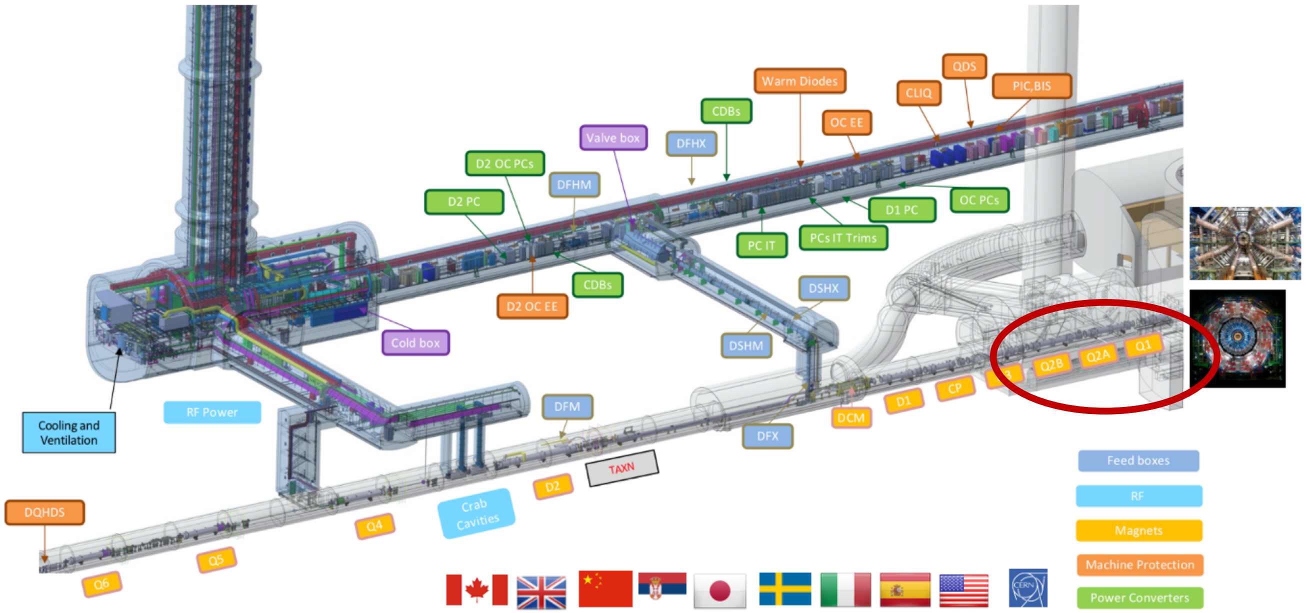
HL-LHC luminosity target: 3000 fb^{-1} to ATLAS and CMS: needed to observe HH production at ~ 5σ level

Injectors upgrade in LS2: to provide beams of intensity and brightness needed for HL-LHC: **2.3×10^{11} p/bunch, ε≃2.1 μm** at LHC injection

Required brightness for multi-bunch LHC beams already achieved (exceeded!) at the Booster



HL-LHC



~ 1.2 km of machine being upgraded with many novel technologies

(new superconducting magnets, crab cavities, low-impedance collimators, crystal collimators, high-T superconducting links, etc.)

> 50% of the project completed

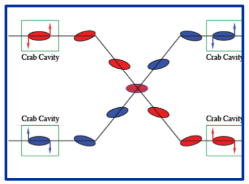
In particular: all civil engineering work done

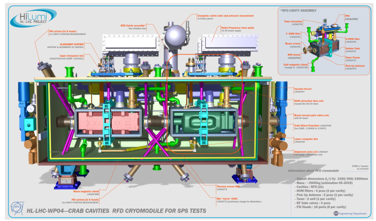
(2 new 300-m service tunnels, 2 shafts, galleries, etc.)

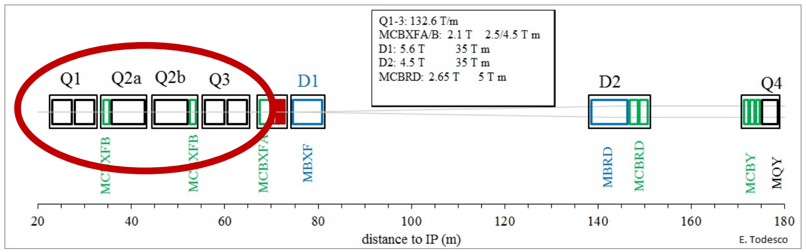
US HL-LHC Accelerator Upgrade Project, AUP

(BNL, FNAL, JLAB, LBNL, Universities):

crab cavities and Nb_3Sn focusing quadrupoles







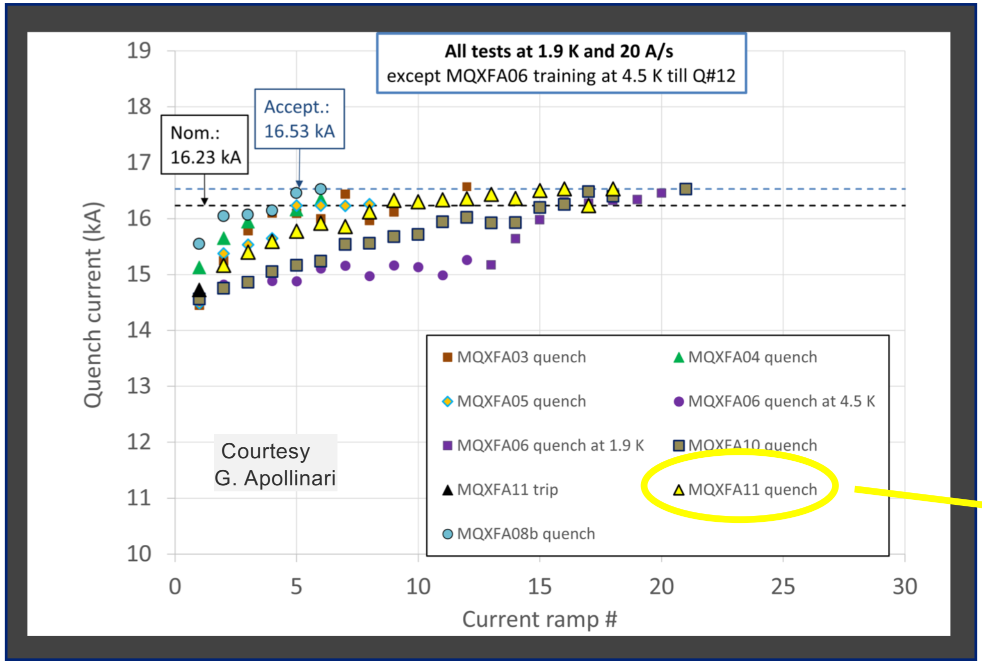
Q1, Q3 (MQXFA): 16 magnets, Nb_3Sn, 4.2-m long, US

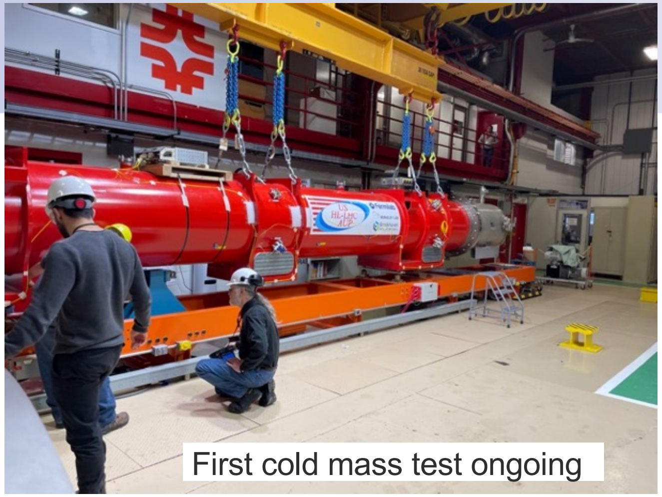
Q2 (MQXFB) : 8 magnets, Nb_3Sn, 7.2-m long, CERN

New Nb_3Sn (12 T at coil) quadrupoles for final focus being built in the US and at CERN

Nb_3Sn quadrupoles in the US

- 9 quadrupoles out of 16 (+ 4 spares) manufactured, 7 tested successfully.
- Endurance test with MQXFA05: after 5 thermal cycles, 52 (42 induced) quenches, 79 power cycles, MQXFA05 reached nominal current at 4.5 K and acceptance current at 1.9 K



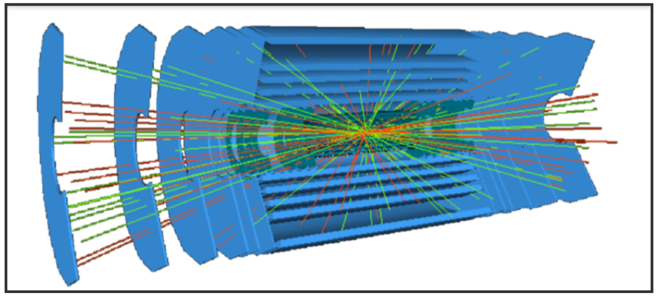


- Great, recent achievements with magnet construction and tests in the US and at CERN
  → Nb_3Sn (very challenging!) technology is now on the way to be mastered
- World's first application of Nb_3Sn magnet technology to operating accelerator
  Essential step towards ~14-16T magnets for future hadron colliders and other applications in our field and beyond
- Excellent example of daily collaboration between US-DOE and CERN (essentially one team)

Note: US HL-LHC AUP based on successful LARP (LHC Accelerator Research Program) directed R&D programme (2005-2015)

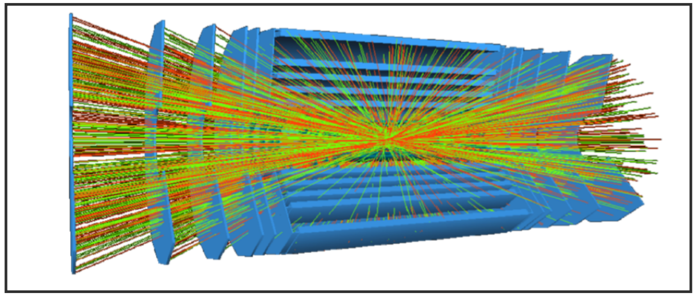
Challenging Phase-2 upgrades of ATLAS and CMS

Higher peak luminosity and larger pile-up (from ~ 30 to 140-200 events/x-ing) require: increased radiation hardness and granularity, dedicated (timing) detectors, larger bandwith, faster and more granular readout electronics, improved triggers, etc.
Strong US participation (DOE, NSF) in most sub-systems.

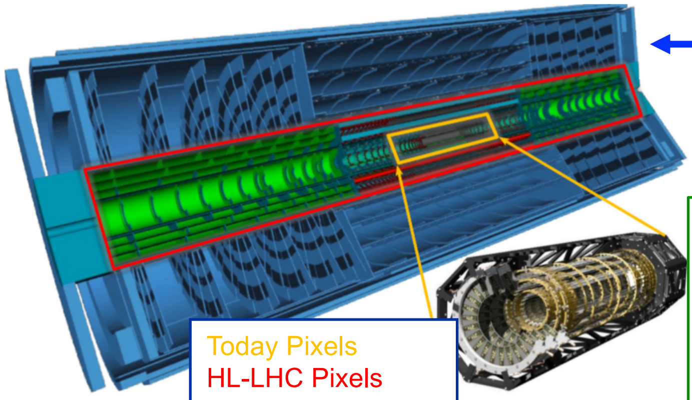


LHC: ~ 30 evts/x-ing

HL-LHC: ~ 140-200 evts/x-ing

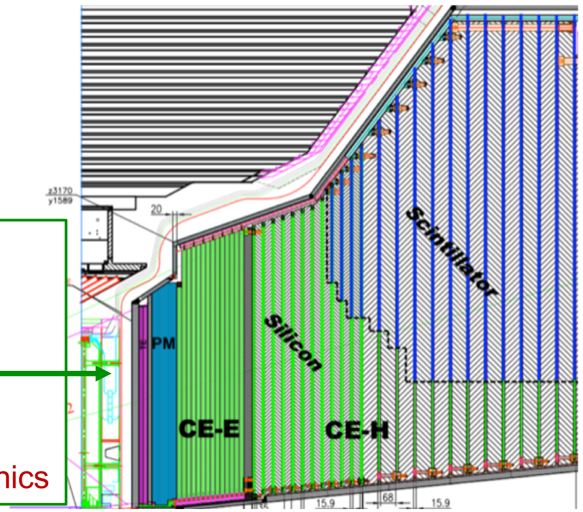


ATLAS tracker (ITk)



$|\eta| < 4$
Low mass, rad hard
Barrel: 5 pixel + 4 strip layers
End-cap: up to 23 pixel + 6 strip rings
Pixel size: 25 x 100 μm^2 and 50 x 50 μm^2
Strip size (barrel): ~ 75 μm x 24-42 mm
Total Si area: ~ 180 m^2
Total # of channels: ~ 5 billion (50 x today)
US: half barrel ITk-strips and Inner ITk-Pixels

CMS end-cap calorimeter (HGCAL)



$1.5 < |\eta| < 3$
Unprecedented transverse/longitudinal segmentation
Time resolution ~ 30 ps
EM (CE-E): Si pads, Cu/CuW/Pb absorber, 26 layers
HAD (CE-H): Si and scintillator, steel absorber, 21 layers
~ 600 m^2 of Si pads (0.5-1 cm^2) 10^6 channles
US: part of CE-E modules, active components of CE-H, electronics

Higgs boson at HL-LHC

H is profoundly different from all elementary particles discovered previously (first elementary scalar?), is related to the most obscure sector of the Standard Model and linked to some of the deepest structural questions (flavour, naturalness/hierarchy, vacuum, ...)

Higgs boson is **an extraordinary discovery tool** and calls for a compelling and broad experimental programme which will extend for decades at the LHC and future facilities.
Note: Higgs boson can only be studied at colliders

Every problem of the SM originates from Higgs interactions

$$\mathcal{L} = \lambda H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

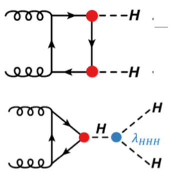
flavour naturalness stability c.c.

G. Giudice

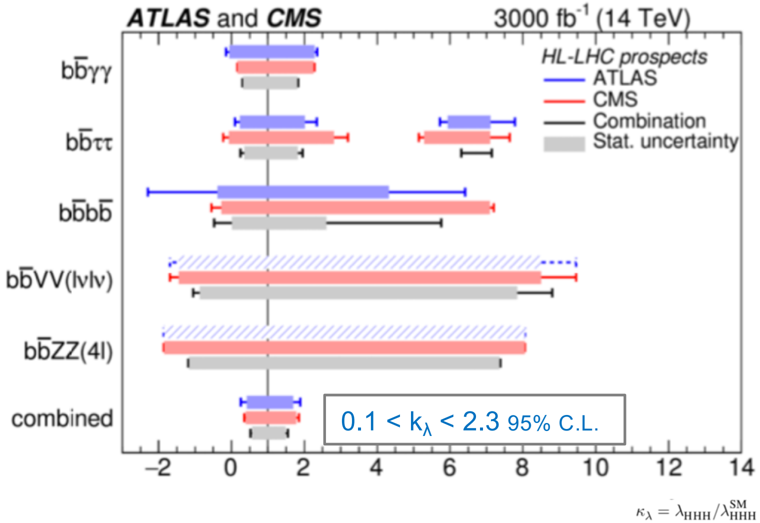
HL-LHC: factor ~ 15 larger data sample than today (3000 fb^{-1}, ~180 M Higgs produced per experiment) and improved detectors
→ significant increase in sensitivity, e.g. rare production and decay modes, differential distributions, searches for additional H, etc.

First observation of HH production within reach at ~ 5σ level

$$\mathcal{L}_h = \frac{1}{2} m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$



Today:
ATLAS : cross-section < 2.4 x SM (2.9 expected), - 0.4 < k_λ < 6.3 95% C.L.
CMS : cross-section < 3.4 x SM (2.5 expected), - 1.24 < k_λ < 6.49 95% C.L.

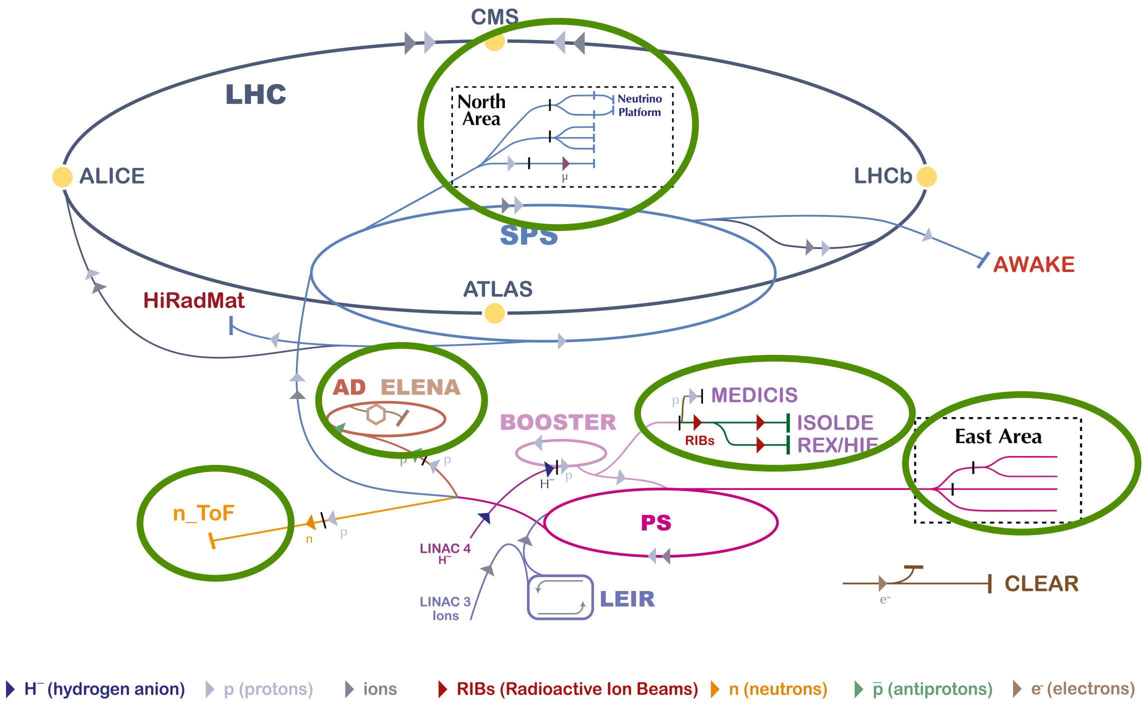


Scientific diversity programme

Scientific diversity programme

~ 2000 physicists

Exploits the unique capabilities of CERN's injectors; complementary to LHC experiments and to other efforts in the world.



Achieved availability in 2022 vs expected

Facility	Destination	Expected 2022 Total [%]	Achieved 2022 Total [%]	Period
LINAC4	-	95	97.1	28.03.2022 – 21.11.2022
PSB	PS	90	95.5	28.03.2022 – 21.11.2022
	ISOLDE		95.5	
PS	SPS	87	89.6	28.03.2022 – 21.11.2022
	nTOF		90.0	
	AD		90.6	
	East Area		91.6	
SPS	LHC	84	89.9	25.04.2022 – 21.11.2022
	North Area		73.2	
	AWAKE		92.3	
	HiRadMat		93.6	

ISOLDE: radioactive nuclei facility; **n-TOF:** n-induced cross-sections; **CLOUD**: impact of cosmic rays on clouds → implications on climate; **AD/ELENA:** Antiproton Decelerator for antimatter studies; **COMPASS**: hadron structure and spectroscopy; **NA61/Shine**: heavy ions and neutrino targets; **NA62**: rare kaon decays; **NA63**: interaction processes in strong EM fields in crystal targets; **NA64**: search for dark photons; **NA65**: τ-neutrino production from D_s decays; **Neutrino Platform: ν** detectors R&D and construction for experiments in US and Japan.

Future opportunities explored within "Physics Beyond Colliders" Study Group.

High-intensity upgrade of North Area beams under study

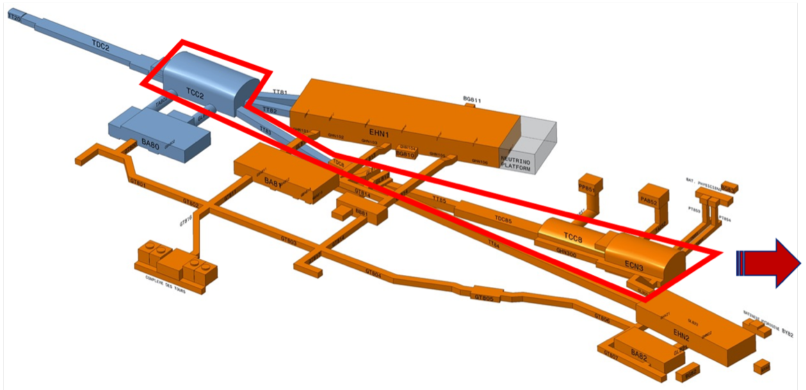
Physics motivations:

- ❑ precision kaon physics: e.g. $K^+ \rightarrow \pi^+\nu\nu$ to 5% (HIKE)
  $K^0_L \rightarrow \pi^0\nu\nu$ to 20% (KLEVER)
- ❑ beam dump experiments for feebly-interacting particle searches (dark photons, heavy neutral leptons, axion-like particles, light dark matter): SHiP, SHADOWS (off-axis, parasitic to HIKE)
- ❑ others? $\tau \rightarrow 3\mu$, …

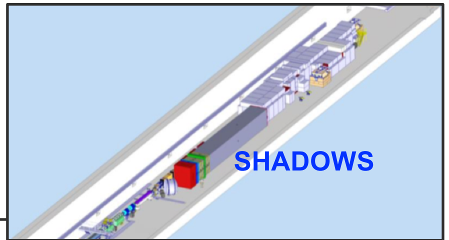
SPS 400 GeV proton beams on target

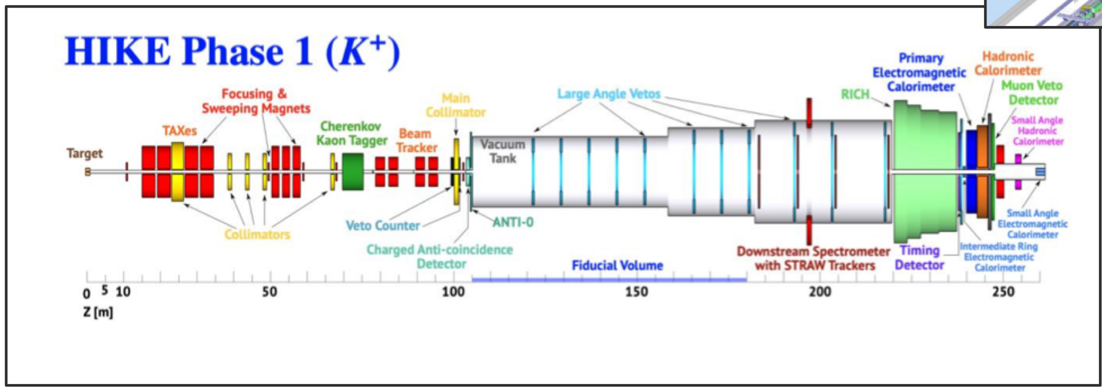
Up to 1.2 (HIKE) - 4 (SHiP) x 10^{19} POT/year: x 6-20 today's intensity

Decision end of 2023 → physics exploitation may start ~ 2030

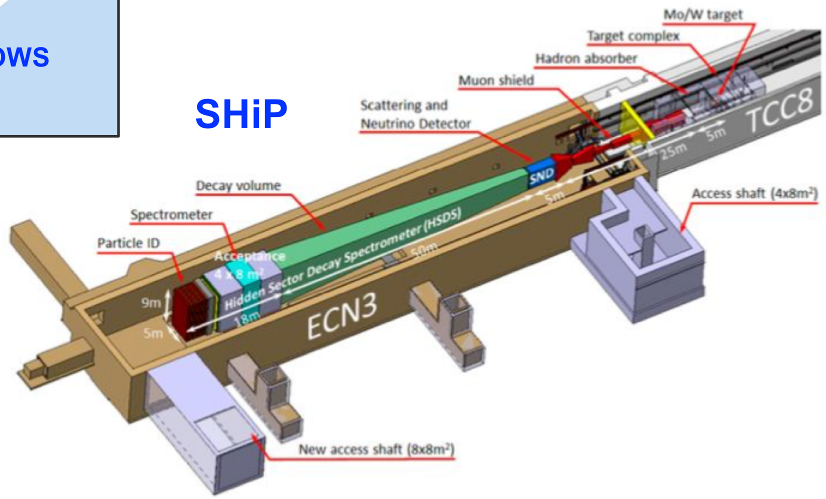


Areas concerned with high intensity beams





SHiP



CERN Neutrino Platform and contributions to LBNF/DUNE

See talk by F. Lanni
at P5 meeting at FNAL

Main historical milestones:

❑ 2013 ESPP update → Neutrino Platform (NP) established in Sep 2013 at CERN

"*CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*"

❑ 2020 ESPP update → priority is on making LBNF/DUNE successful → CERN decided to provide second cryostat for LBNF/DUNE

"Europe, and CERN through the NP, should continue to support long-baseline experiments in Japan and the United States. In particular, they should continue to collaborate with the US and other international partners for the successful implementation of LBNF/DUNE"

Main US-related activities at the NP since 2013:

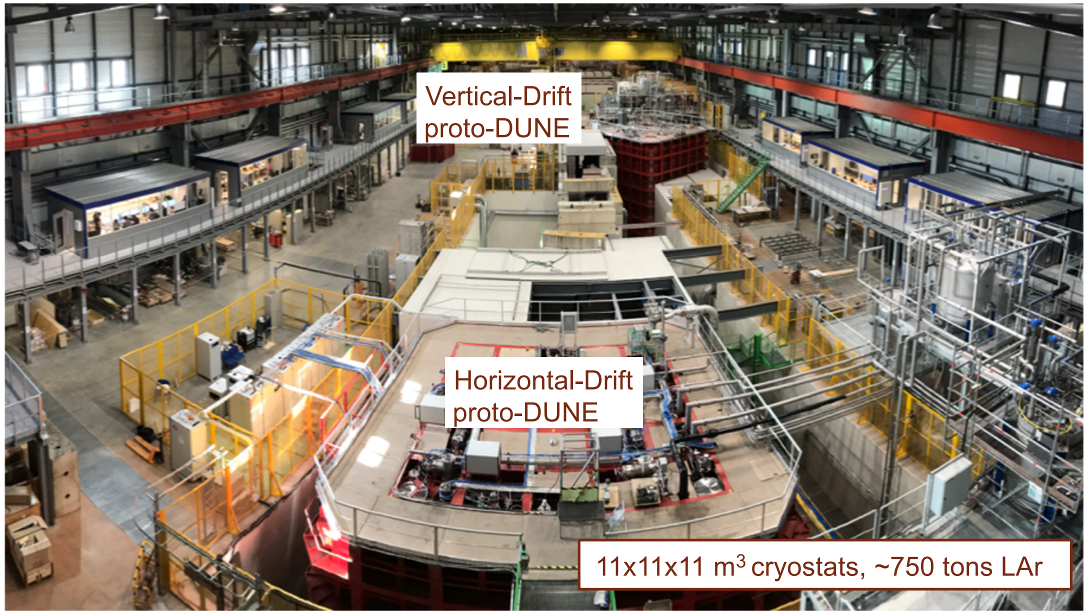
❑ Extensions of EHN1 hall at North Area to provide space and beam facility for ν detectors

❑ Refurbishment of ICARUS detector for short-baseline neutrino programme at Fermilab

❑ R&D, construction and operation of 2 prototypes for DUNE (single-phase/horizontal drift; dual-phase → vertical-drift).
Now preparing for tests of "modules-zero".

→ This work has been crucial to bring LAr TPC technology for large-scale detectors from R&D to maturity, demonstrate detector feasibility, and finalise technical choices.

❑ Contributions to LBNF/DUNE construction:
- infrastructure: 2 cryostats
- detectors: HV system, Charge Readout Planes for vertical-drift module, Readout, Reconstruction and Trigger system, etc.
- intellectual and leadership roles in LBNF/DUNE design
- possible contributions to Phase-2 detectors (not discussed yet).



NP today: ~ 900 collaborators from ~30 countries (~ 65% from Europe)

Preparation of CERN’s future

From ESPP 2020 update

"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."

⬇

FCC Feasibility Study (FS) started in 2021 → will be completed in 2025

"The European particle physics community should develop an accelerator R&D roadmap focused on the critical technologies needed for future colliders" …. "The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs."

⬇

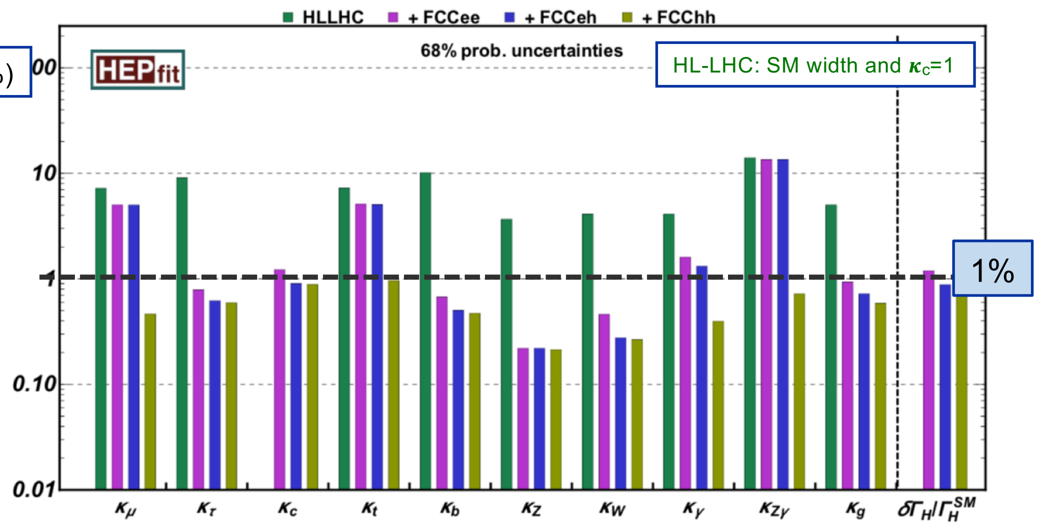
Accelerator R&D roadmap developed (→ now being executed). CERN pursue R&D on high-field magnets, SCRF, proton-driven plasma wakefield acceleration, and R&D and design studies for CLIC and muon colliders to prepare alternative options to FCC if the latter is not pursued.

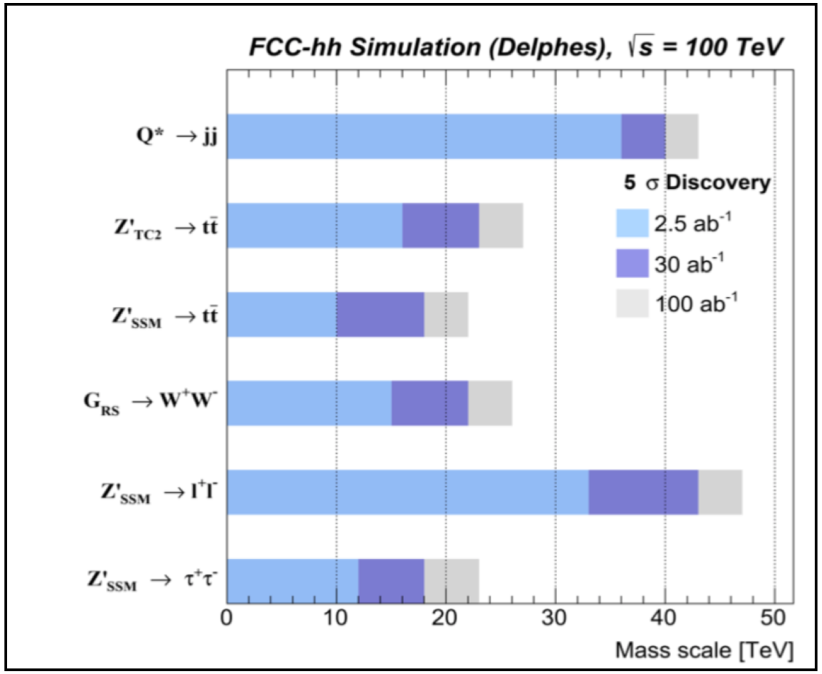
FCC physics potential

	√s	L /IP ($cm^{-2} s^{-1}$)	Int L/IP/y (ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV Z 160 WW 240 H ~365 top	182 x 10^{34} 19.4 7.3 1.33	22 2.3 0.9 0.16	2-4 experiments Total ~ 15 years of operation
pp **FCC-hh**	100 TeV	5 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb **FCC-hh**	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep **Fcc-eh**	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb **Fcc-eh**	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

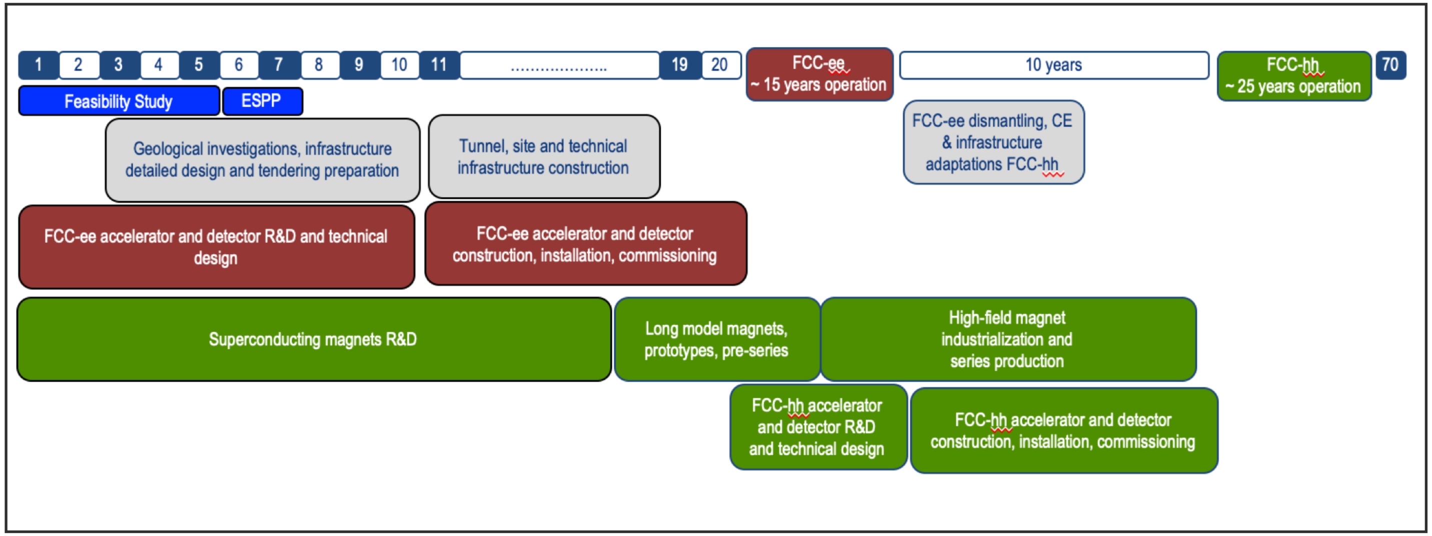
A multi-stage facility with immense physics potential (energy and intensity), operating until the end of the century.

- FCC-ee : highest luminosities at Z, W, ZH of all proposed Higgs and EW factories; indirect discovery potential up to ~ 70 TeV
- FCC-hh: direct exploration of next energy frontier (~ x10 LHC) and unparalleled measurements of low-rate and "heavy" Higgs couplings (ttH, HH)
- Also heavy-ion collisions and, possibly, ep/e-ion collisions
- Synergistic programme exploiting common civil engineering and technical infrastructure, building on and reusing CERN's existing infrastructure

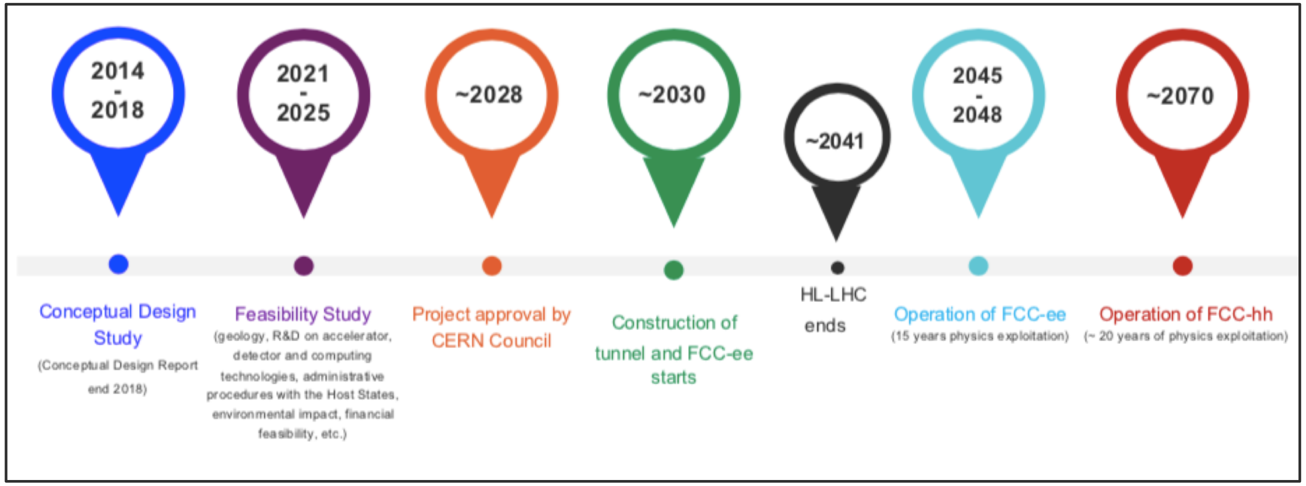




FCC estimated timeline



Technical schedule:
FCC-ee could start operation **in 2040 or earlier**



Realistic schedule takes into account:
- ❑ past experience in building colliders at CERN
- ❑ CERN Council approval timeline
- ❑ that HL-LHC will run until ~ 2041

→ **ANY future collider at CERN cannot start physics operation before 2045-2048** (but construction will proceed in parallel to HL-LHC operation)

FCC-ee: main machine parameters

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

- 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: main machine parameters for pp

Parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	80-116		14	14
dipole field [T]	14 (Nb_3Sn) – 20 (HTS/Hybrid)		8.33	8.33
circumference [km]	90.7		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2700		7.3	3.6
SR power / length [W/m/ap.]	32.1		0.33	0.17
long. emit. damping time [h]	0.45		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	7.8		0.7	0.36
integrated luminosity [fb^{-1}]	20000		3000	300

Formidable challenges:

- high-field superconducting magnets: 14 - 20 T
- power load in arcs from synchrotron radiation: 5 MW → cryogenics, vacuum
- stored beam energy: 8 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

FCC Feasibility Study 2021-2025: main objectives

- Demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure

- Pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval

- Optimisation of the design of FCC-ee and FCC-hh colliders and their injector chains, supported by R&D to develop the needed key technologies

- Elaboration of a sustainable operational model for the machine and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency

- Development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation (emphasis on FCC-ee).
  Current cost estimate from 2018 CDR (https://fcc-cdr.web.cern.ch): 12 BCHF for tunnel and FCC-ee; 17 BCHF for FCC-hh

- Identification of substantial resources from outside CERN's budget for the implementation of first stage project (tunnel and FCC-ee)

- Consolidation of the physics case and detector concepts and technologies

Feasibility Study funded from CERN budget (~ **35 MCHF/year** over 5 years, including high-field magnet R&D).
Additional funding from the European Commission and collaborating institutes (e.g. CHART collaboration with Switzerland)

Mid-term review end of 2023 → final results in Feasibility Study Report by end of 2025

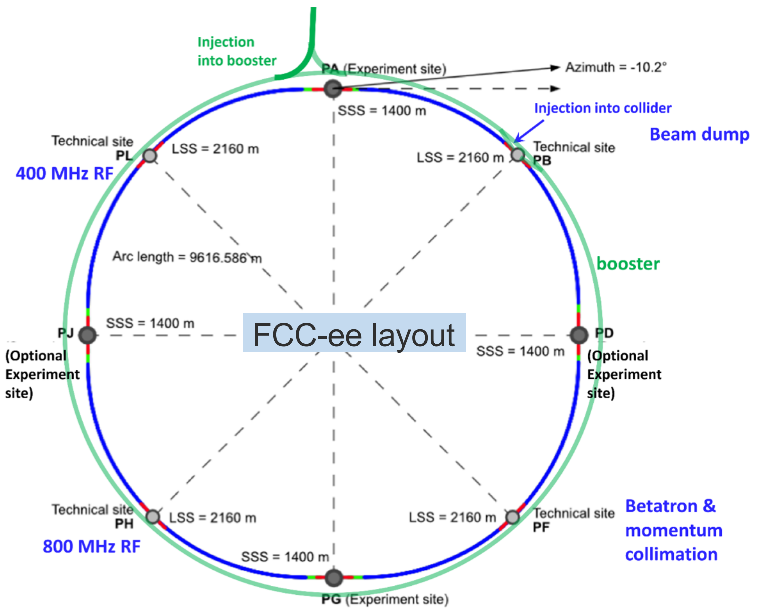
FCC Feasibility Study 2021-2025: progress (example)

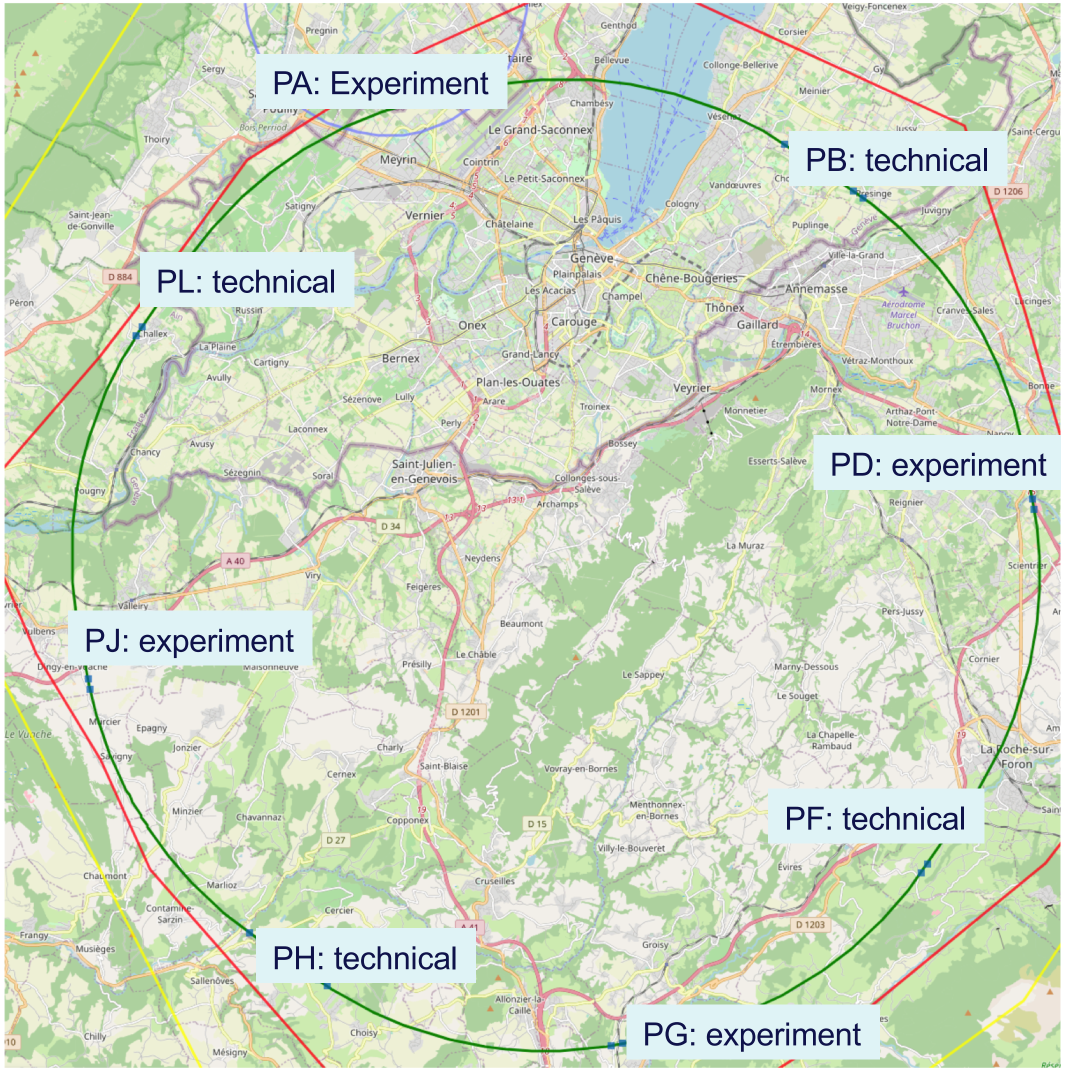
Major achievement: selection of the ring placement

Layout chosen out of ~ 50 initial variants, based on geology and surface constraints (land availability, access to roads, etc.), environment (protected zones), infrastructure (water, electricity, transport), etc.
"Éviter, reduire, compenser" principle of EU and French regulations

Baseline ring: 90.7 km ring, 8 surface points

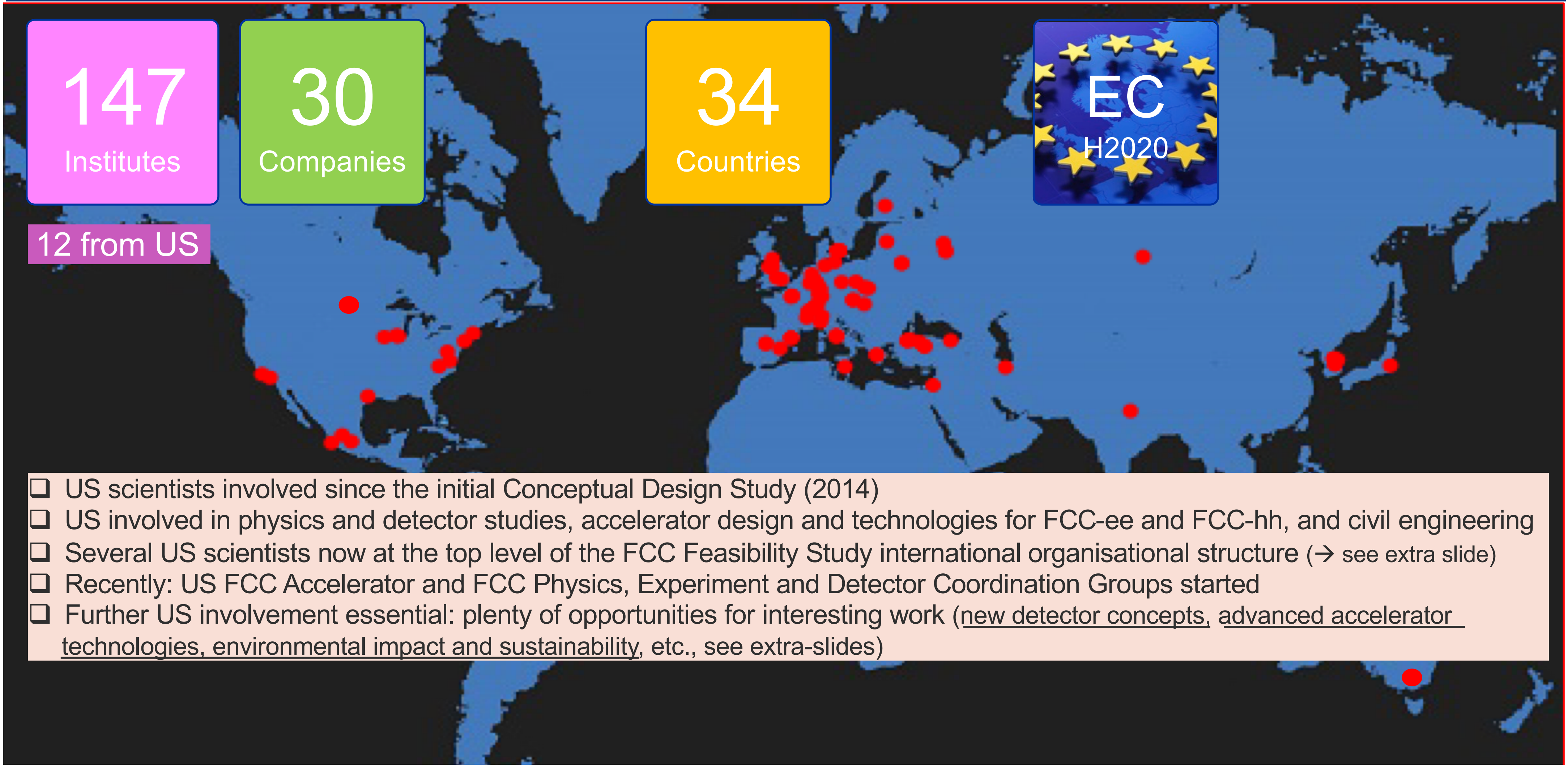
- ❑ Whole project now being adapted to this placement
- ❑ Site investigation: 9 areas with uncertain geological conditions to be further investigated (~40 drillings and 100 km of seismic lines)





FCC Collaboration

FUTURE CIRCULAR COLLIDER



- US scientists involved since the initial Conceptual Design Study (2014)
- US involved in physics and detector studies, accelerator design and technologies for FCC-ee and FCC-hh, and civil engineering
- Several US scientists now at the top level of the FCC Feasibility Study international organisational structure (→ see extra slide)
- Recently: US FCC Accelerator and FCC Physics, Experiment and Detector Coordination Groups started
- Further US involvement essential: plenty of opportunities for interesting work (new detector concepts, advanced accelerator technologies, environmental impact and sustainability, etc., see extra-slides)

Alternative scenarios: CLIC and muon colliders goals 2021-2025

CLIC goals:
- ❑ finalise X-band technology towards construction readiness (accelerating structure's conditioning and manufacturing)
- ❑ improve power efficiency (e.g. klystrons) → recently from 170 to 110 MW
- ❑ optimise luminosity for first-stage machine and nanobeam technology (beam dynamic studies, machine alignment and stability, etc.)
  → recently 1.5 improvement

→ "**Project Readiness Report**" by end 2025 (as input to next ESPP)

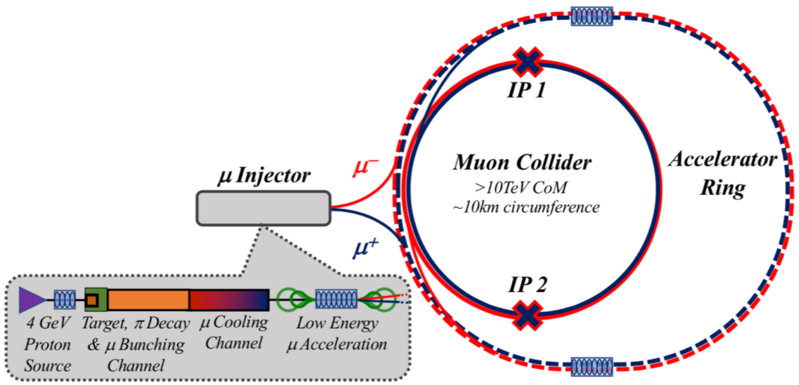
Note: CERN contributes to a possible **ILC** in Japan through collaboration on technologies and studies of interest for CLIC and ILC, participation in ILC committeees (IDT and its WGs) and coordination of Europe's involvement in ILC

Parameter	Unit	Stage 1	Stage 2	Stage 3
$\sqrt{s}$	GeV	380	1500	3000
Tunnel length	km	11	29	50
Gradient	MV/m	72	72/100	72/100
Pulse length	ns	244	244	244
Luminosity (above 99% of $\sqrt{s}$)	10^{34} cm^{-2}s^{-1}	1.5 0.9	3.7 1.4	5.9 2
Repetition frequency	Hz	50	50	50
Bunches per train		352	312	312
Bunch spacing	ns	0.5	0.5	0.5
Particles/bunch	10^9	5.2	3.7	3.7
Beam size at IP (σ_y/σ_x)	nm	2.9/149	1.5/60	1/40
Annual energy consumption	TWh	0.8	1.7	2.8
Power consumption	MW	170	370	590
Construction cost	BCH	5.9	+5.1	+7.3

Muon collider's goals: work on main challenges, including muon source and cooling, fast-ramping magnets, accelerator and collider rings, neutrino background and civil engineering
→ determine by end 2025 (as input to next ESPP) if **investment in muon collider demonstrator** programme and CDR **are justified** from scientific perspective.

International study initially hosted by CERN; resources allocated from CERN's budget.

Recently: 3 M€ from a European Commission grant



Conclusions

CERN has a compelling, broad scientific programme:

- ❑ LHC and HL-LHC, which will be operating at the E-frontier until 2041
- ❑ facilities and experiments at the injectors, complementary to the collider, serving a broad community (including neutrinos)
- ❑ vigorous R&D and design studies for future facilities

To ensure CERN's future and maintain and motivate the community (especially the young people):

- ❑ successful completion of HL-LHC and experiments' upgrades is crucial → demonstrate the continued ability of the community to execute ambitious, large-scale projects; attract the young people to the very rich HL-LHC programme
- ❑ physics at a new facility at CERN should start within a few years of the end of HL-LHC

The 2020 update of the European Strategy identified a Higgs factory as the highest-priority next collider and FCC as the preferred option for a future collider at CERN. FCC has immense physics potential but is also a very challenging and ambitious project. Feasibility Study will be completed at the end of 2025. Substantial resources allocated; plenty of opportunities for very interesting work.

FCC will only be possible with a strong US participation (people, ideas, technologies, resources) → important to support directed R&D for FCC accelerators (à la LARP) and detectors, feeding into a possible future project, so as to allow the US community to contribute to shaping the project from the outset.

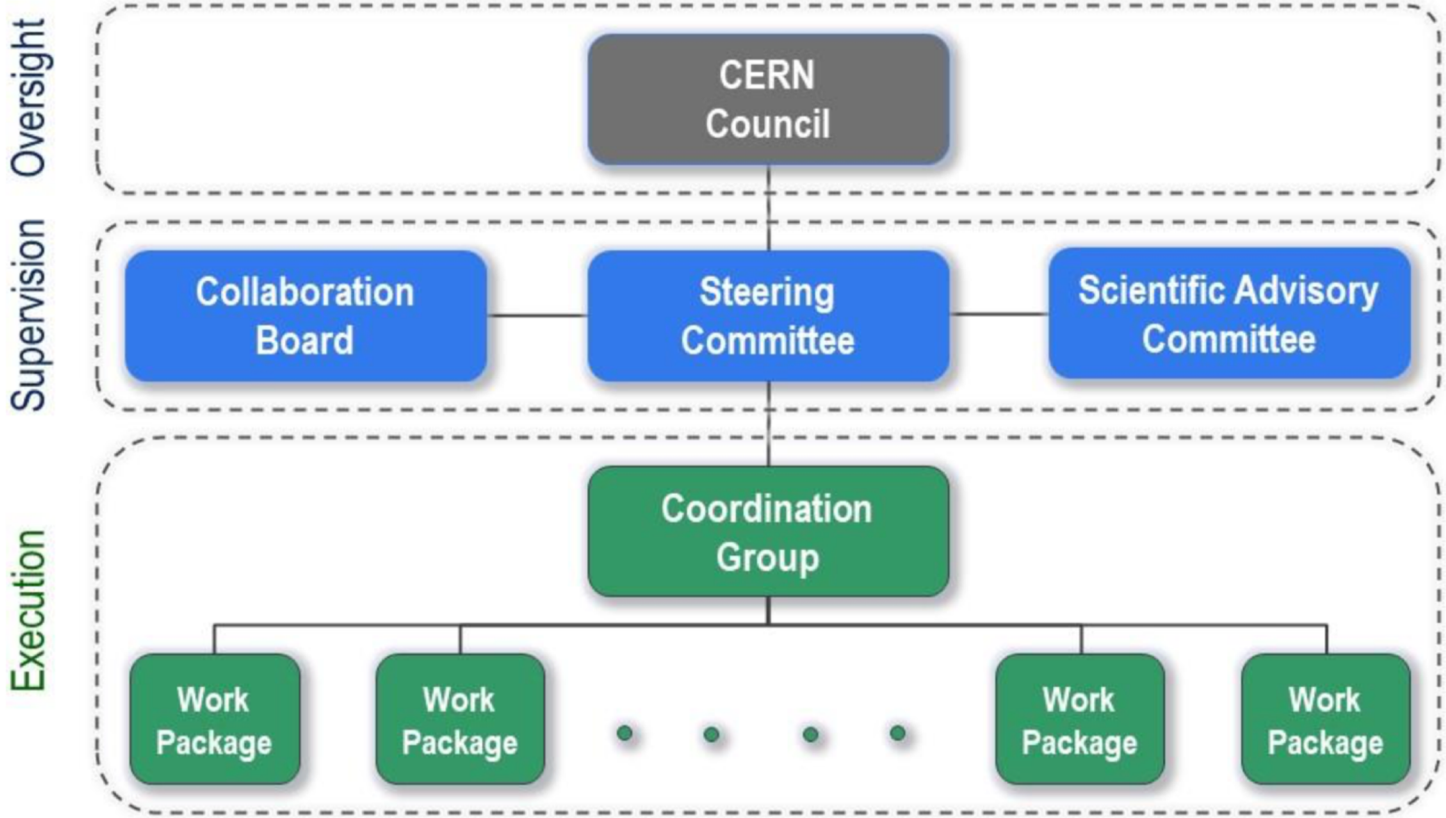
CERN is committed to the success of LBNF/DUNE and other ongoing collaborations with the US, and ready to discuss cooperation on other future projects in the US (EIC, …).

The cooperation between the US and CERN/Europe and the coherence of our strategies (following SSC cancellation → US joined the E-frontier at the LHC; following 2014 P5 report → CERN decided to discontinue long/short baseline beams in Europe to contribute to LBNF/DUNE) have been very beneficial to the field so far and are also crucial for the future.

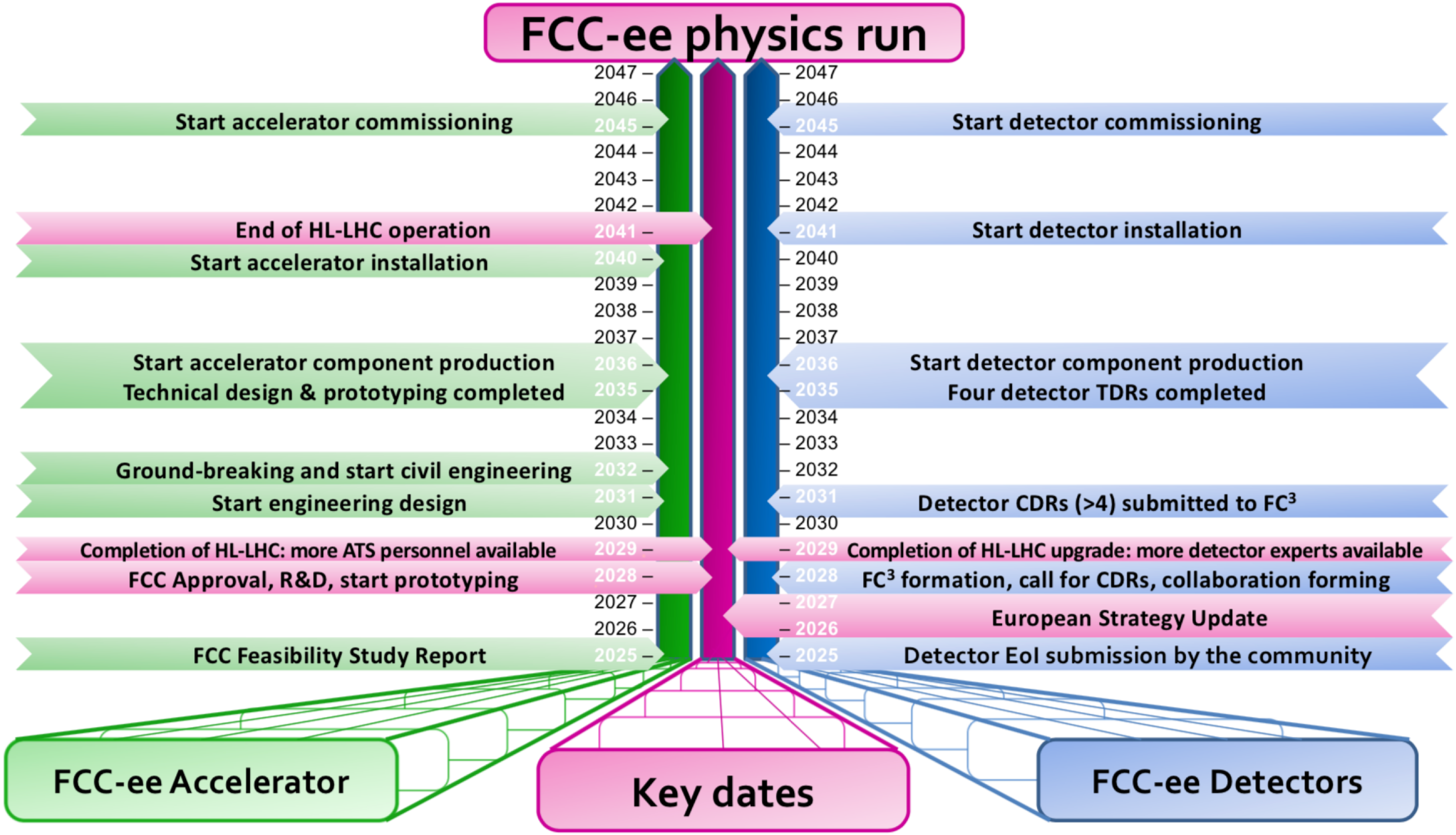
The destinies of US-HEP and CERN are closely coupled

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) is co-convener of Accelerators Work Package and member of Coordination group
Michiko Minty (BNL) is member of Scientific Advisory Committee


FCC-ee physics run
Start accelerator commissioning
End of HL-LHC operation
Start accelerator installation
Start accelerator component production
Technical design & prototyping completed
Ground-breaking and start civil engineering
Start engineering design
Completion of HL-LHC: more ATS personnel available
FCC Approval, R&D, start prototyping
FCC Feasibility Study Report
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Start detector commissioning
Start detector installation
Start detector component production
Four detector TDRs completed
Detector CDRs (>4) submitted to FC³
Completion of HL-LHC upgrade: more detector experts available
FC³ formation, call for CDRs, collaboration forming
European Strategy Update
Detector EoI submission by the community
FCC-ee Accelerator
Key dates
FCC-ee Detectors

US involvement in FCC (selection)

- Physics and detector studies (numerous US universities and labs)
- high-field magnet development (FNAL, LBNL, NHFML)
- SRF development (800 MHz 5-cell cavity prototype, JLAB)
- FCC-ee accelerator design: optics and collective effects (SLAC)
- FCC-ee machine detector interface (SLAC, BNL, JLAB)
- FCC-ee interaction-region magnet systems (BNL)
- FCC-ee polarisation and precise energy calibration (FNAL, BNL, Cornell, UNM)
- FCC-EIC collaborations (BNL, JLAB)
- FCC tunnel safety (FNAL)
- FCC civil engineering - surface building design (FNAL)
- SRF 800 MHz bulk Nb cavities with high-Q – in preparation
- SRF cryomodule design – in preparation

FCC-ee and Electron-Ion Collider (EIC)

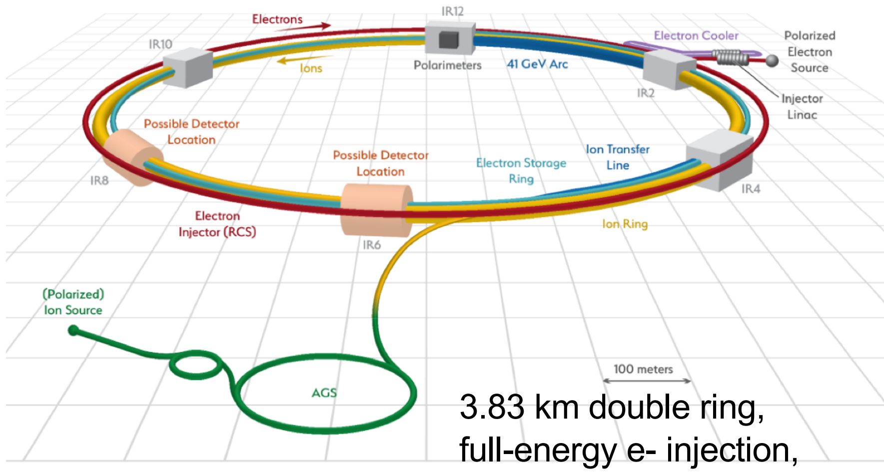
US EIC Electron Storage Ring similar to, but more challenging than, FCC-ee

beam parameters almost identical, but twice the maximum electron beam current, or half the bunch spacing, and lower beam energy

>10 areas of common interest identified by the FCC and EIC design teams, addressed through **joint EIC-FCC working groups**

EIC will start beam operation about a decade prior to FCC-ee

The EIC will provide another invaluable opportunity to train next generation of accelerator physicists on an operating collider, to test hardware prototypes, beam control schemes, etc.

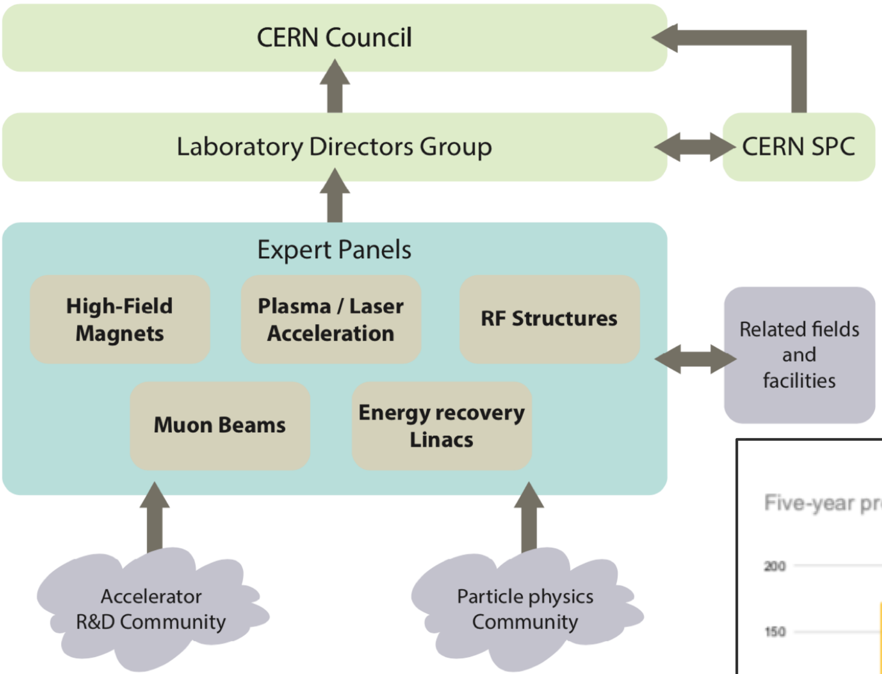


3.83 km double ring, full-energy e- injection, injection rate 1 Hz

	EIC	FCC-ee-Z
Beam energy [GeV]	**10 (18)**	**45.6 (80)**
Bunch population [10^{11}]	**1.7**	**1.7**
Bunch spacing [ns]	**10**	**15, 17.5 or 20**
Beam current [A]	**2.5 (0.27)**	**1.39**
SR power / beam /meter [W/m]	**7000**	600
Critical photon energy [keV]	**9 (54)**	**19 (100)**

European Accelerator R&D roadmap

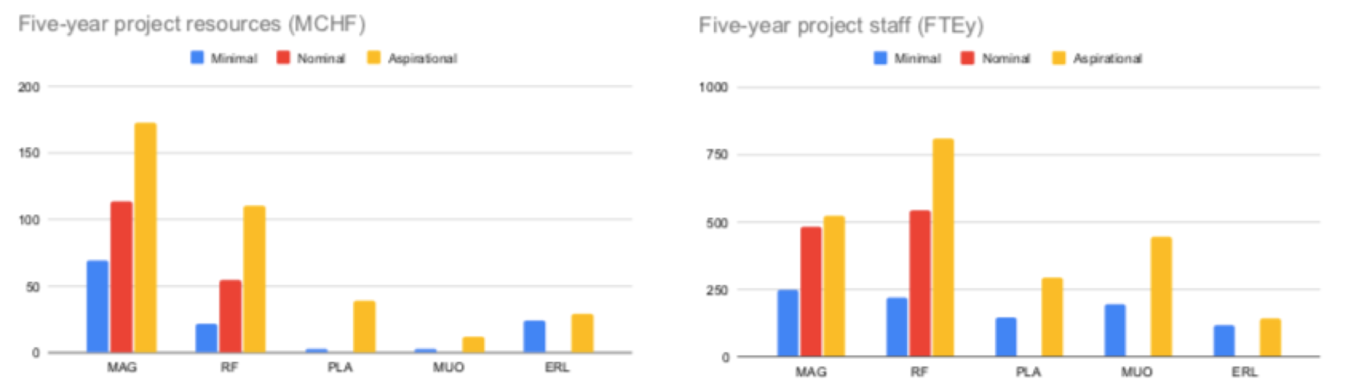
Following ESPP recommendation, roadmap developed (with US participation) → approved by CERN's Council Dec. 2021.
https://cds.cern.ch/record/2800190/files/2201.07895.pdf
Organisational structures for implementation in place



CERN contributes in significant way to four of five areas,
and supports ERL studies on best-effort basis.
In particular:

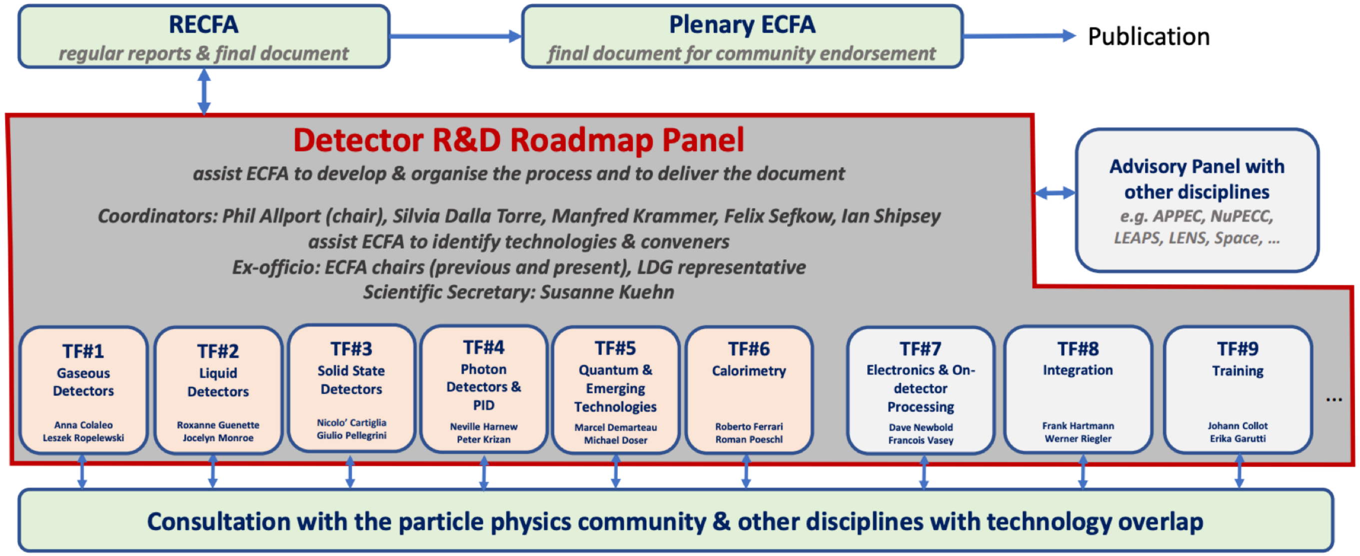
- CERN high-field magnet programme funded with significant resources; strong network of collaborating lab in Europe and beyond
- AWAKE experiment: proton-driven plasma wakefield
- RF work mainly targeting current and future colliders (HL-LHC, FCC-ee, CLIC, muon colliders)
- International muon collider study hosted by CERN

Current funding corresponds to minimal scenario



Detector R&D roadmap

Roadmap developed (with US participation) and approved by CERN’s Council Dec. 2021
https://cds.cern.ch/record/2784893/files/ECFA%20Detector%20R&D%20Roadmap.pdf



Implementation plans being developed and organisational structures (DRD- Detector R&D Collaborations hosted by CERN) being established.
Continued collaboration with the US is crucial.

In addition, 10 General Strategic Recommendations:
Supporting R&D facilities; Engineering support for detector R&D; Specific software for instrumentation; international coordination and organisation of R&D activities; Distributed R&D activities with centralized facilities; Establish long-term strategic funding programmes; Blue-Sky R&D; Attract, nurture, recognize and sustain the careers of R&D experts; Industry partnership; Open Science.

CERN Quantum Technology Initiative

12 areas of work have been established across Theory, Computing, Sensing and Communications.

More than 20 post-doc and doctoral projects are in place and have generated **32 publications** and conference presentations.

Collaborations with companies in France, Israel, Spain, Switzerland, UK have been established, more being discussed for 2023.

A proposal for **QTI Phase 2** is being prepared with a focus on a subset of activities where CERN can have measurable impact.

Launch of Open Quantum Institute incubator in Geneva with CERN as a founding member

Successful QT4HEP Conference in November, more than 250 attendees. A working group on Quantum Technology for HEP has been formed with participation from HEP Institutes in EU, US, Japan and other countries showing the impact that CERN is having in the field.

Now working on a joint programme across the HEP community to be completed in Spring 2023