CERN’s vision and plans

Fabiola Gianotti (CERN)
Snowmass-Seattle, 25 July 2022

CERN in few numbers

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

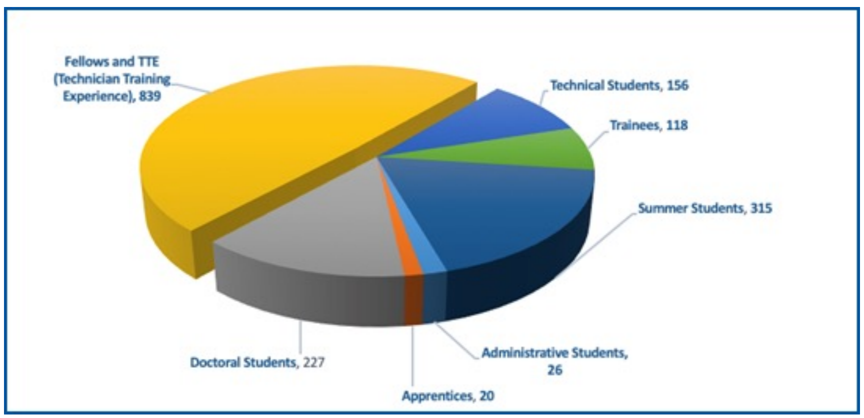
Annual Budget: 1.3 BCHF (shared by Member States based on net national income)
~ 580 MCHF spent annually for procurements (supplies, services)

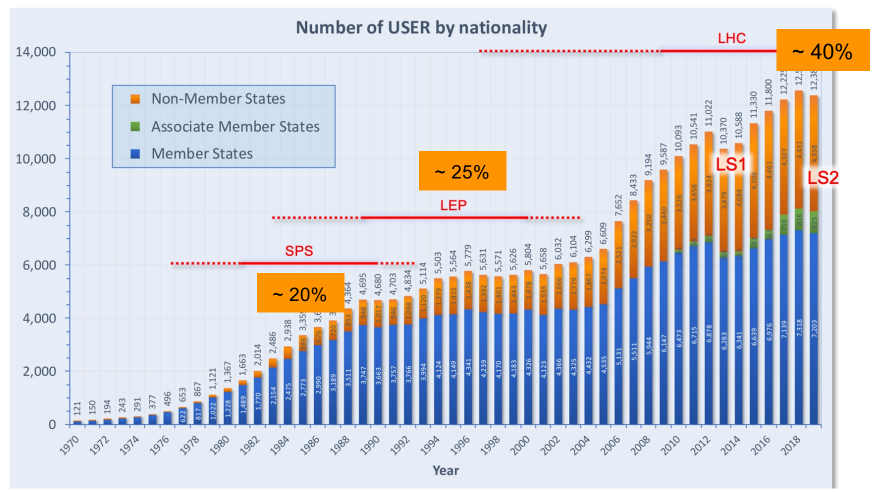
Every year (pre-Covid-19):
150000 visitors to CERN
4 million visitors to CERN website
150000 press cuttings
2 million mentions on social media

CERN's community: > 16000 people (> 110 nationalities)

- ❑ 2700 staff
- ❑ 800 post-doctoral fellows
- ❑ 12700 users and other associates
- ❑ 3000 PhD students from all over the world
- ❑ 4500 young people trained at CERN at any time
- ❑ US population: 2045 scientists 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 everyday (before Covid-19)





Initial remarks

The contributions of DOE, NSF and US scientists (~17% of CERN's users),
in particular the intellectual contributions of the young scientists,
have been crucial to the success of the LHC and CERN more generally.

They will continue to be crucial also in the future for HL-LHC and beyond.
In particular, FCC (or any other future collider at CERN) will only be possible with the strong participation of the US community (ideas, technologies, resources).

Likewise, CERN is committed to support LBNF/DUNE and open to discuss collaboration on future projects in the US.

CERN's scientific strategy and programme based on 3 pillars

Full exploitation of the LHC:
- ❑ successful Run 3: $\sqrt{s}$ =13.6 TeV; integrated luminosities: 250 fb^{-1} (ATLAS and CMS), 25-30 fb^{-1} (LHCb), 7 nb^{-1} (ALICE, Pb-Pb)
- ❑ High-Luminosity LHC upgrade (construction underway) → starts in 2029 ends ~ 2042 (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, East Area)
- ❑ participation in accelerator-based neutrino projects outside Europe (presently mainly LBNF/DUNE) through Neutrino Platform
- ❑ future opportunities discussed within "Physics Beyond Colliders" study group

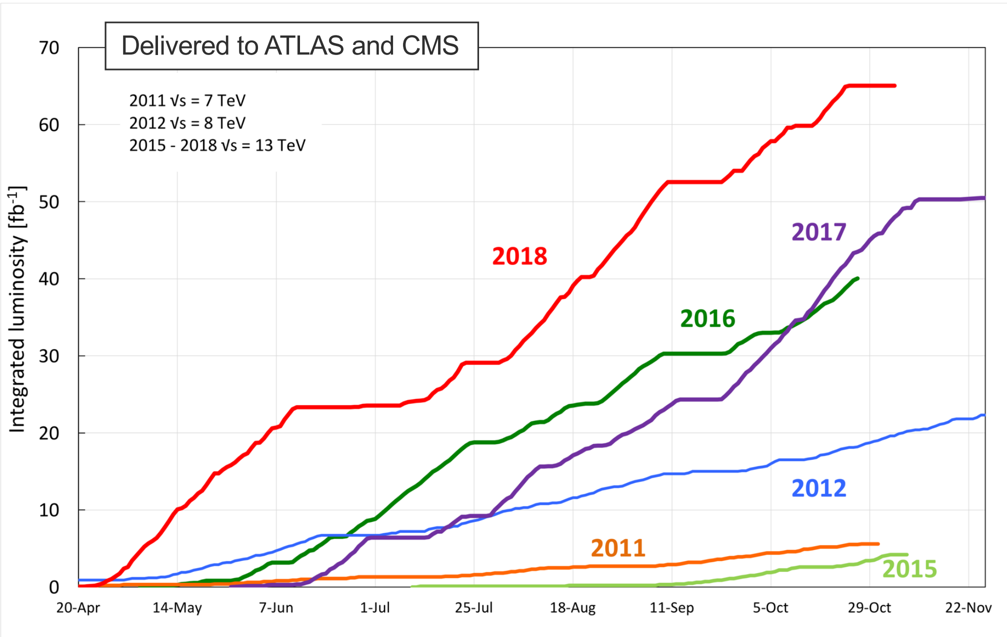
Preparation of CERN's future:
- ❑ intense accelerator R&D programme (including superconducting high-field magnets, RF, plasma wakefield, etc.)
- ❑ Future Circular Collider (FCC) Feasibility Study → final report end 2025
- ❑ R&D and design studies for other scenarios: CLIC, muon colliders

Based on 2020 update of the European Strategy for Particle Physics (ESPP)

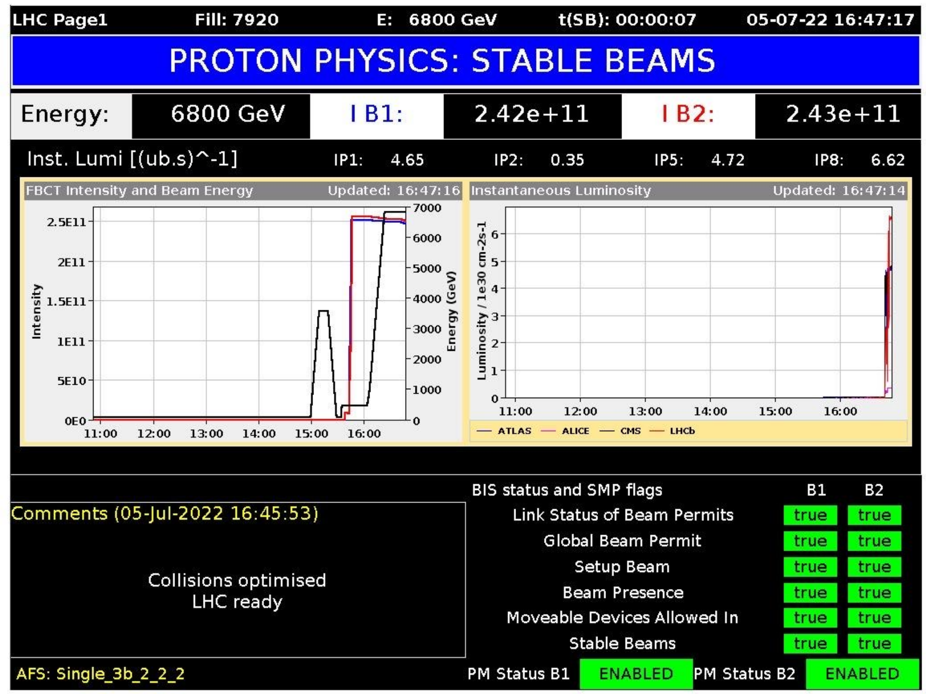
Note: next ESPP update expected in ~ 2026-2027 → assume input to be submitted end 2025

LHC and HL-LHC

LHC : a success story



Run 3 started on 5 July with first collisions at 13.6 TeV

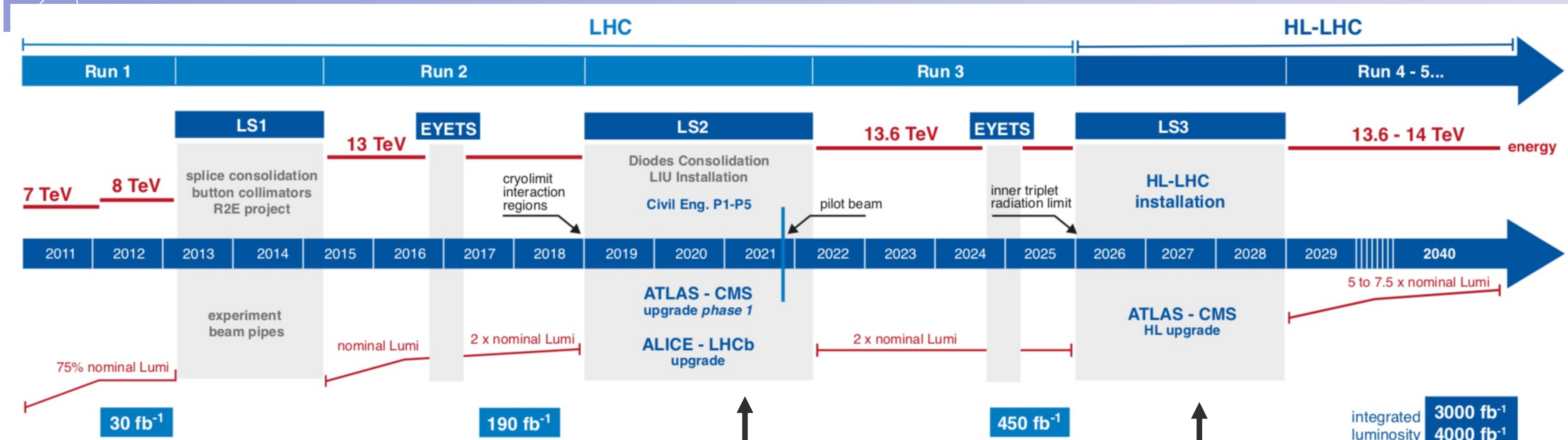


Achieved peak luminosity Run 2 : 2×10^{34} cm^{-2} s^{-1} (x2 design value)

Run 1 (2010-2012) delivered: ~ 30 fb^{-1} at 7-8 TeV
Run 2 (2015-2018) delivered: ~ 160 fb^{-1} at 13 TeV
Run 3 (2022-2025) expected: ~ 250 fb^{-1} at 13.6 TeV

Run 1+2 luminosity (189 fb^{-1}) **is only 6%** of total integrated luminosity expected at the end of HL-LHC

High-Luminosity LHC (HL-LHC)



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

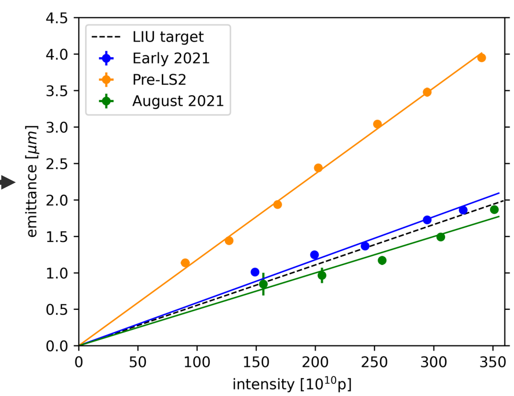
LS3
Installation of HL-LHC machine
Phase-2 upgrades of ATLAS and CMS

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

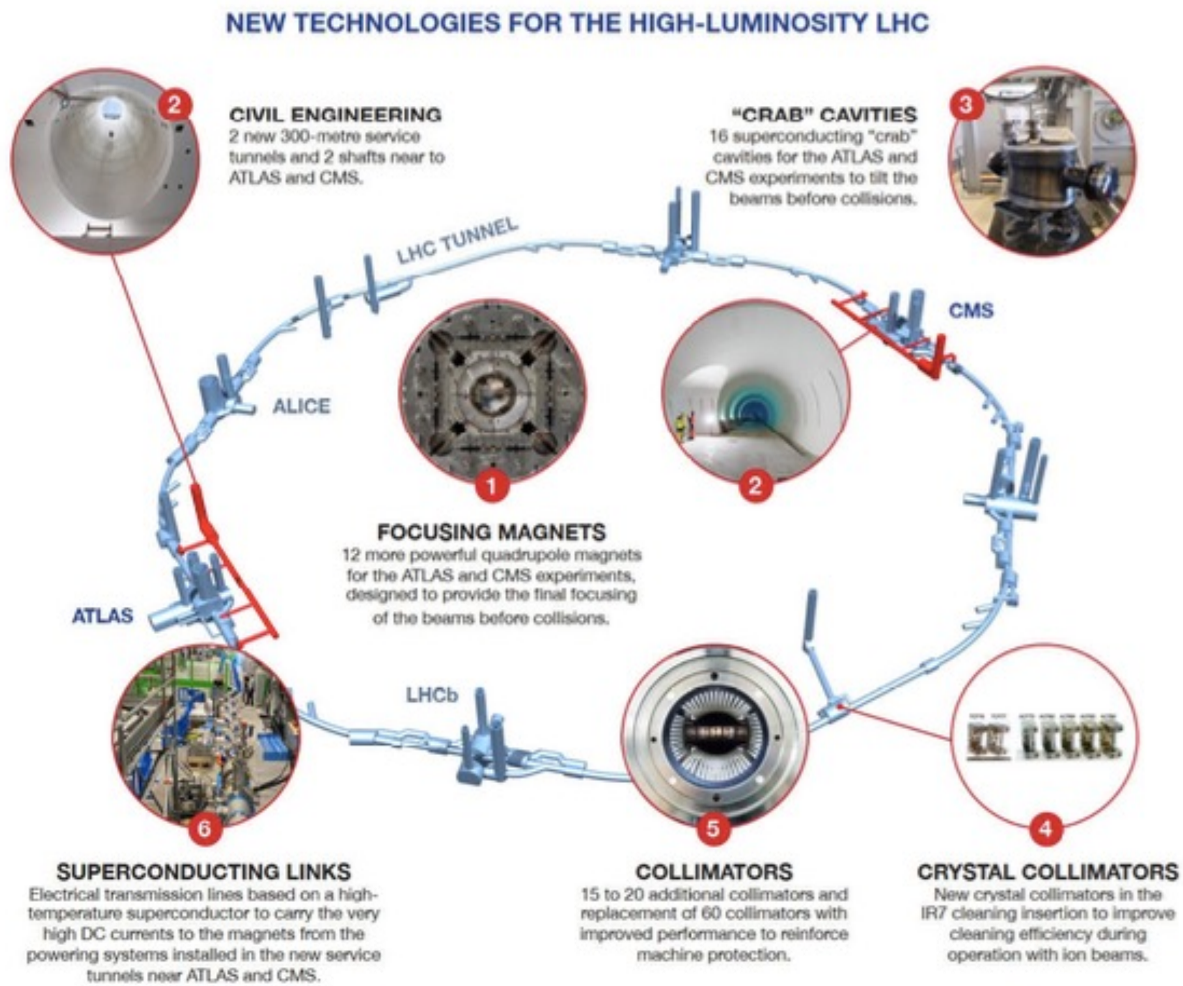
Injectors upgrade in LS2: to provide beams of intensity and brightness needed for HL-LHC: **2.3×10^{11} p/bunch, ε~ 2.1 μm** at LHC injection

Excellent performance upon restart in 2021 → target parameters needed for HL-LHC already achieved/exceeded in some cases

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



HL-LHC



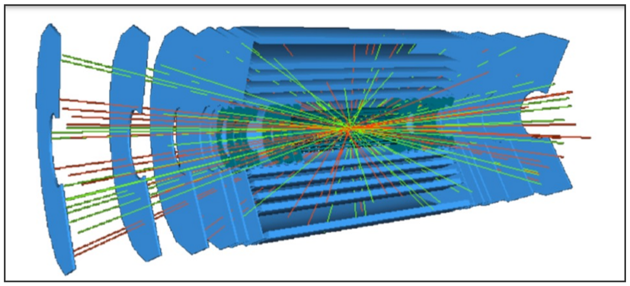
~ 1.2 km of machine being upgraded with many novel technologies.

~ 50% of the project completed
In particular, all underground civil engineering work completed during LS2.
Prototypes completed and production started for many components

New Nb_3Sn quadrupoles (12 T) for final focus:
4 full-length (4.2 m) magnets successfully built and tested in the US;
2 full length (7.2 m) magnets did not achieve nominal current at CERN (learned a lot from work done over past months to understand causes)
Essential step towards ~ 16T magnets for future hadron colliders and other applications in our field and beyond

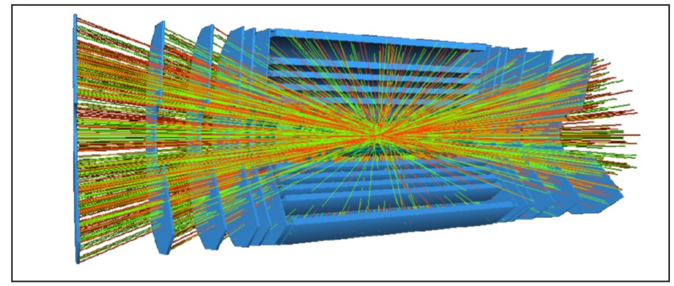
Challenging Phase-2 upgrades of ATLAS and CMS

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.

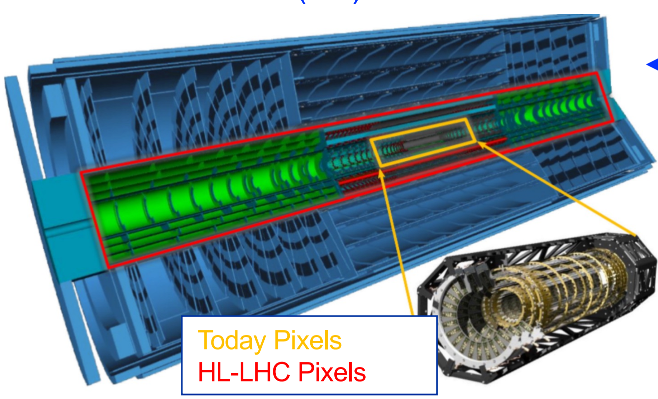


LHC: ~ 30 evts/x-ing

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



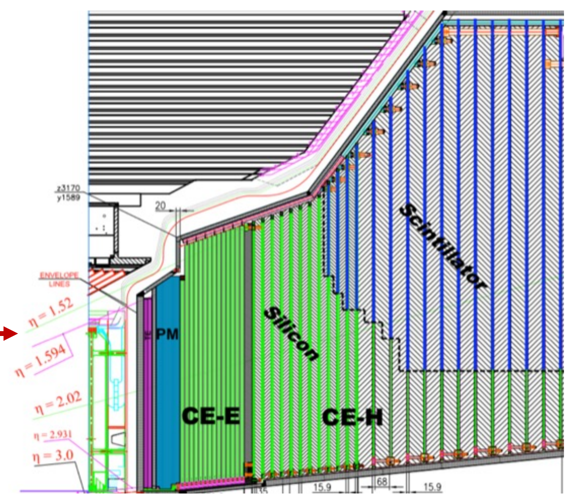
ATLAS tracker (ITk)



$|\eta| < 4$
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)

CMS end-cap calorimeter (HGCAL)

$1.5 < |\eta| < 3$
Unprecedented lat. and long. 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



Higgs boson physics at current and future colliders

Discovery of the Higgs boson: monumental step forward in our understanding of fundamental physics, with wide-ranging implications for particle physics and beyond

Higgs boson 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, ...)

G. Giudice

Every problem of the SM originates from Higgs interactions

$$\underset{\uparrow\ \text{flavour}}{\mathcal{L} = \lambda H \psi \bar{\psi}} + \underset{\uparrow\ \text{naturalness}}{\mu^2 |H|^2} - \underset{\uparrow\ \text{stability}}{\lambda |H|^4} - \underset{\uparrow\ \text{c.c.}}{V_0}$$

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 beyond.
"Study it to death" – N. Arkani-Hamed
Note: Higgs boson can only be studied at colliders

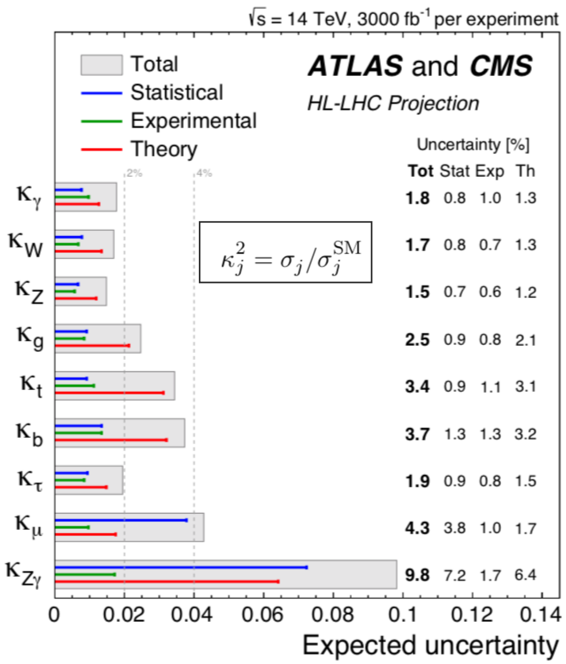
Current Higgs boson knowledge from LHC (numbers are per experiment).
Note: some of these measurements were not expected to be possible in Run 2

- All main Higgs boson production modes (ggF, VBF, VH, ttH+tH) established at > 5σ
- Couplings to gauge bosons (established in Run 1) measured to 6-8%
  Couplings to 3rd generation fermions, top, b and τ (established in Run 2) measured to 7-11%
  Couplings to 2nd generation fermions: 3σ evidence for H→ μμ; first constraints on H→ cc
- Rare decays (e.g. H→ Zγ; H→ llγ at ~ 3σ level). Limits on invisible and exotic decays
- HH production: sensitivity x 3 SM cross-section
- Mass measured to ~ 0.1%; width measurement from off-shell/on-shell production demonstrated (3.6σ evidence for H off-shell production)
- $J^{CP}=0^{++}$ (large number of alternative hypotheses excluded > 99.9% C.L.)
- Inclusive studies complemented by increasing variety of differential/exclusive measurements (useful to constrain theory; provide additional constraints on couplings; sensitive to new physics in quantum loops affecting kinematic distributions)
- Searches for additional Higgs bosons (no sign yet …)
- Etc. etc.

Higgs boson at HL-LHC

Factor ~ 20 larger data sample than today (3000 fb^{-1}, ~180 M Higgs produced per experiment) and improved detectors
→ significant increase in sensitivity

Higgs couplings measurements

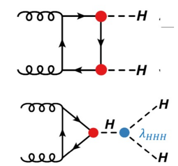


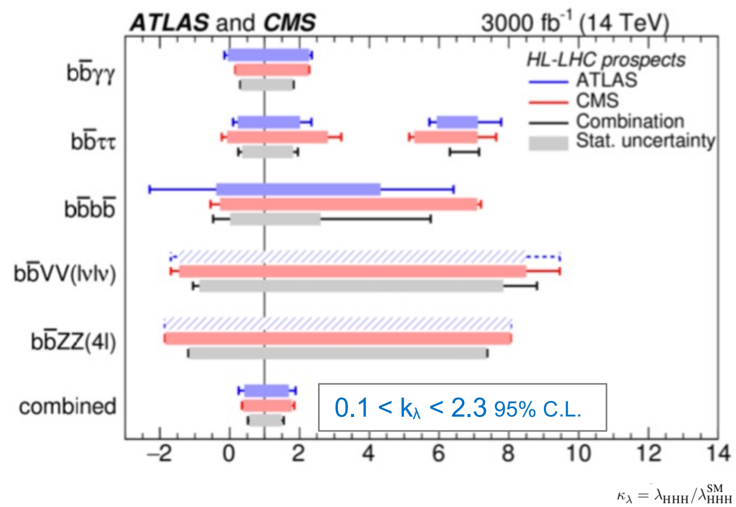
Global fit assuming no BSM contributions to $\Gamma_{H.}$

- ❑ 3-4 times more precise than today
- ❑ first 5σ observation of H→ Zγ (H→ μμ already in Run 3)
- ❑ experimental precision challenges theory

First observation of HH production (~ 5σ level)

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





Today:

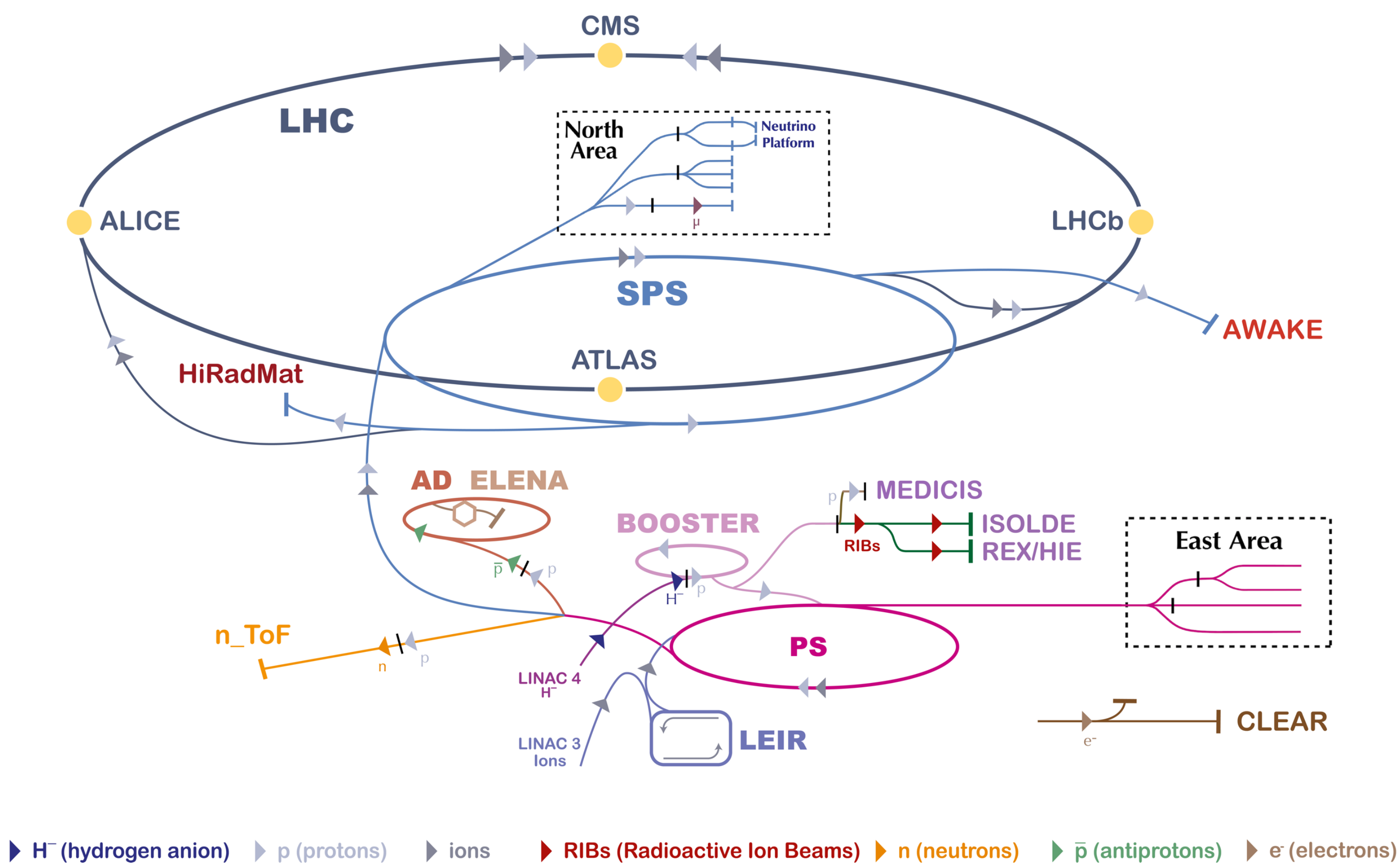
ATLAS : cross-section < 2.4 x SM (2.9 expected), - 0.6 < k_λ < 6.6 95% C.L.

CMS : cross-section < 3.4 x SM (2.5 expected), - 1.24 < k_λ < 6.49 95% C.L.

Scientific diversity

Scientific diversity programme

~20 projects, ~ 2000 physicists



AD/ELENA: Antiproton Decelerator for antimatter studies

CAST, OSQAR: axions

CLOUD: impact of cosmic rays on clouds → implications on climate

COMPASS: hadron structure and spectroscopy

ISOLDE: radioactive nuclei facility

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

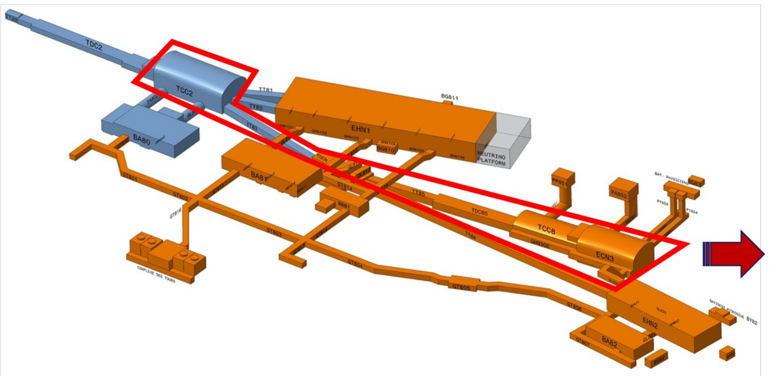
Neutrino Platform: ν detectors R&D for experiments in US, Japan

n-TOF: n-induced cross-sections

UA9: crystal collimation

Exploits unique capabilities of CERN’s injectors; complementary to LHC experiments and to other efforts in the world.
Future opportunities being explored within “Physics Beyond Colliders” Study Group.

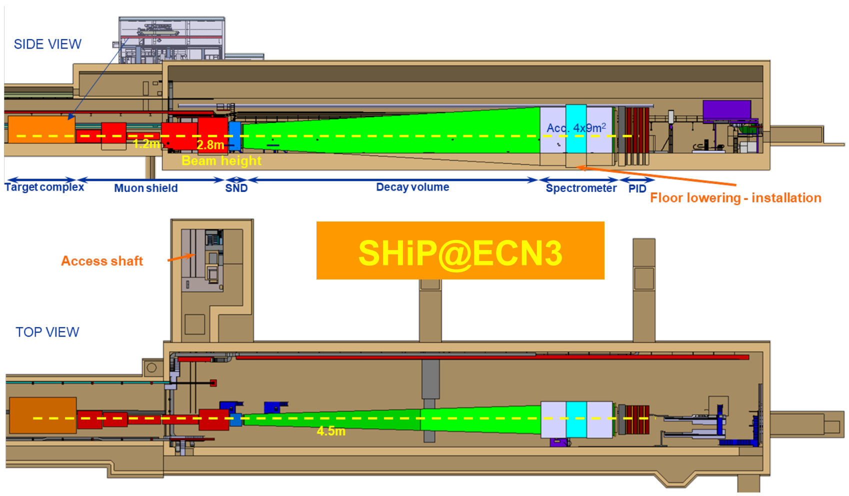
Consolidation Phase 1 (funded): 2019 – 2027

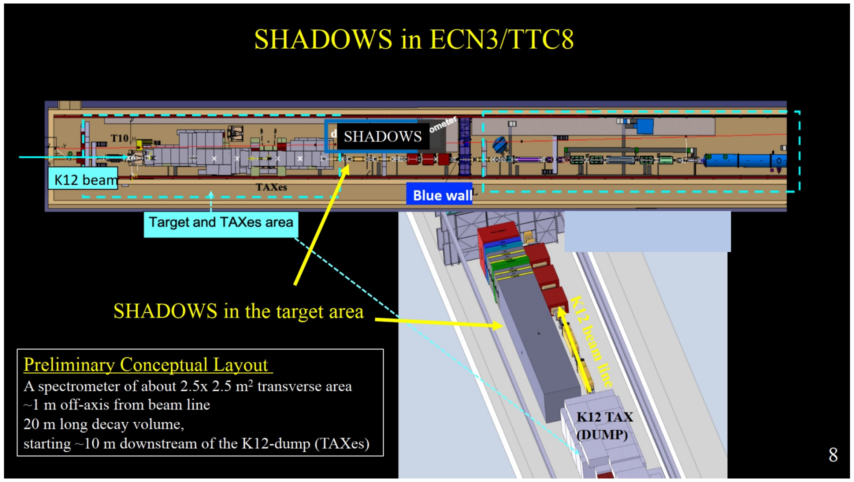


North Area upgrade to higher-intensity beams:
up to ~ 4 x 10^{19} POT/year (slow extraction) possible post-LS3
Current interest: kaon physics (HIKE), beam dump experiments for dark sector and other studies (SHADOW, SHiP), τ → 3μ (TauFV), …

Areas concerned with high intensity beams

Consolidation Phase 2 (not yet funded): 2028 – 2033





CERN Neutrino Platform

Established in 2014, following 2013 update of ESPP:
"*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.*"

Main activities at the NP since the beginning

- ❑ 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
- ❑ Construction and operation of two prototypes for DUNE (single-phase; dual-phase → vertical-drift technology)

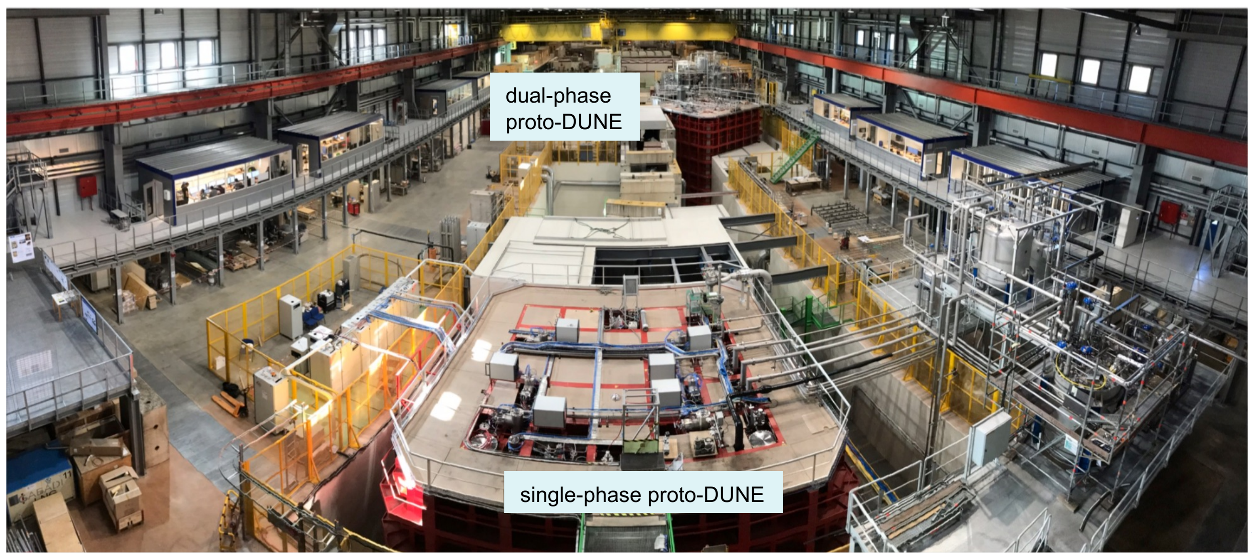
→ crucial to establish detector feasibility, validate technology and finalise technical choices

- ❑ Construction of cryostats for two (out of four) modules of DUNE
- ❑ Construction of Baby-Mind and ND280 upgrade detectors for the T2K experiment in Japan

With ~ 900 collaborators from ~30 countries

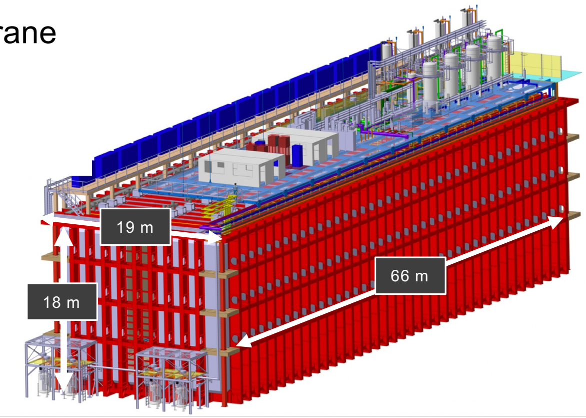
Construction and test of two DUNE detector prototypes at CERN's Neutrino Platform:

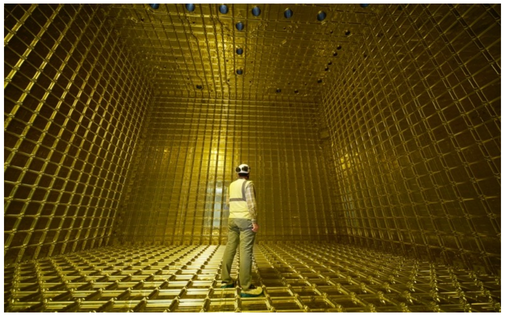
- ❑ 11x11x11 m^3 cryostat
- ❑ ~750 tons LAr each
- ❑ 1 DUNE module: x 20 proto-DUNE



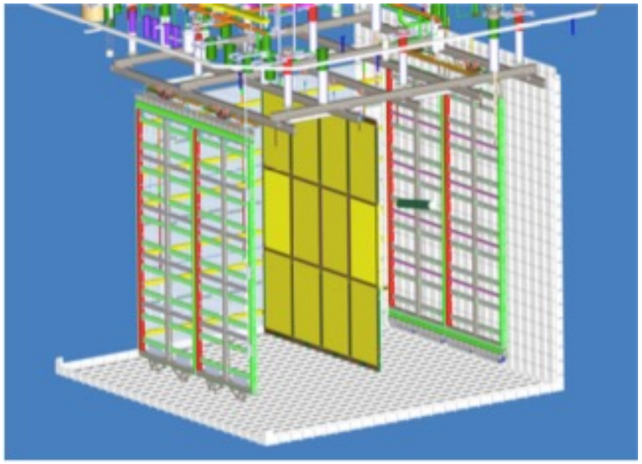
CERN Neutrino Platform: current LBNF-related activities

Construction of two cryostats for LBNF/DUNE based on membrane technology (used for over sea transport of liquid natural gas).
Design completed, procurement and manufacturing started
→ *in situ* installation at SURF 2024-2027

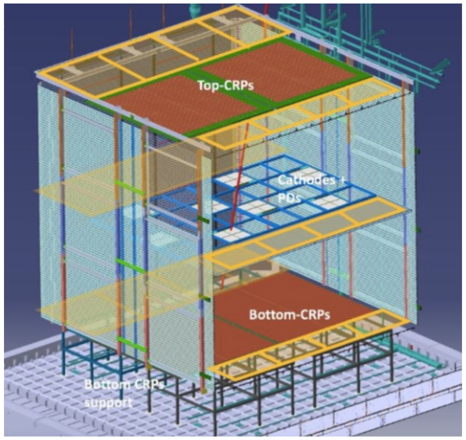




Single-phase proto-DUNE II "module zero" : horizontal drift.
To test final component designs (APA, cold electronics, cryogenics, calibration, etc.) → beam test in NP04 cryostat Autumn 2022-Spring 2023



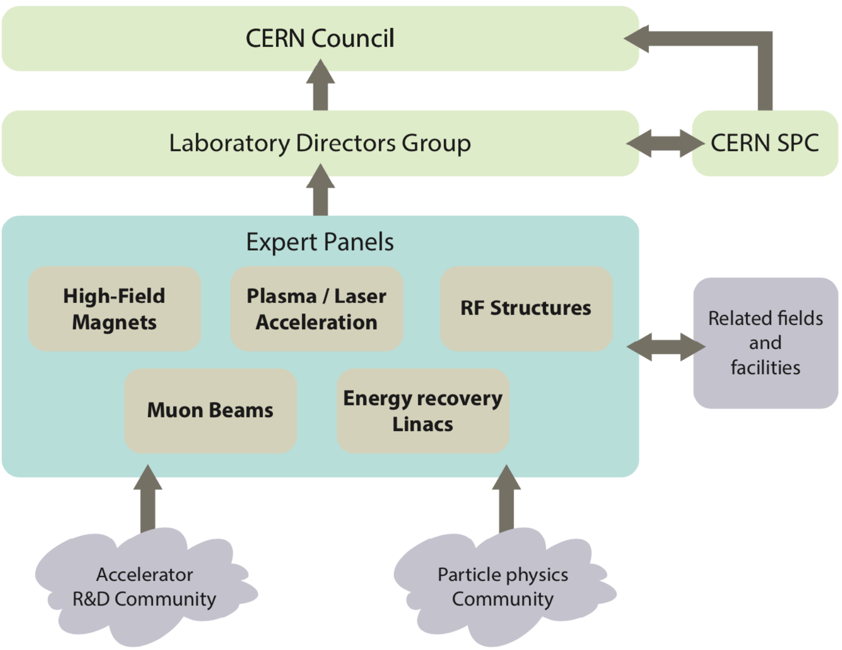
Vertical-drift module zero's construction and test:
Successful test of HV=300 kV in NP02 cryostats and of charge readout planes in small cold box.
Module-zero beam test in NP02 cryostat second half 2023



Preparation of CERN's future

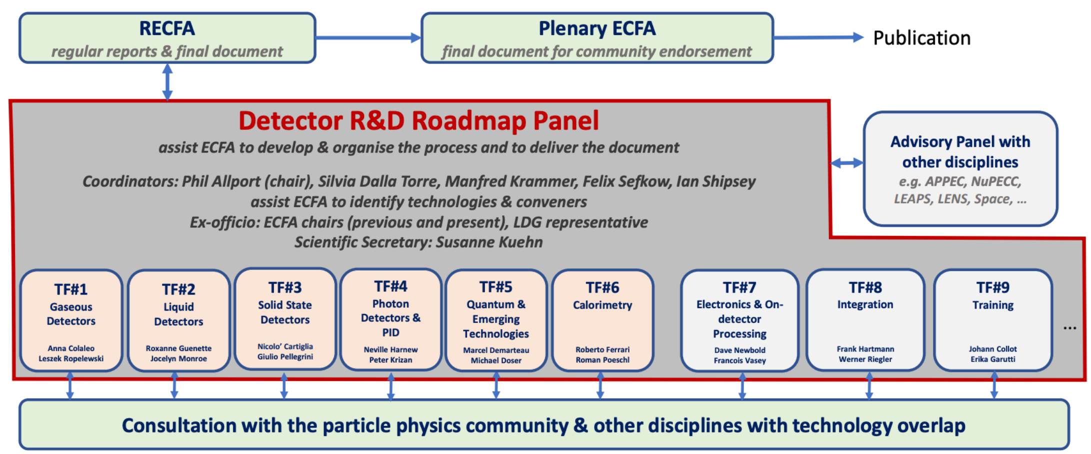
Accelerator and Detector R&D

Following ESPP recommendation, roadmaps developed in Europe (with US participation) → approved by CERN's Council Dec. 2021



Implementation plans being developed and organizational structures being established (US participation in these collaborations would be very much welcome).

Investment in R&D is essential for the future of the field!



FCC Feasibility Study 2021-2025

2020 ESPP 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

FCC Feasibility Study 2021-2025

FUTURE CIRCULAR COLLIDER

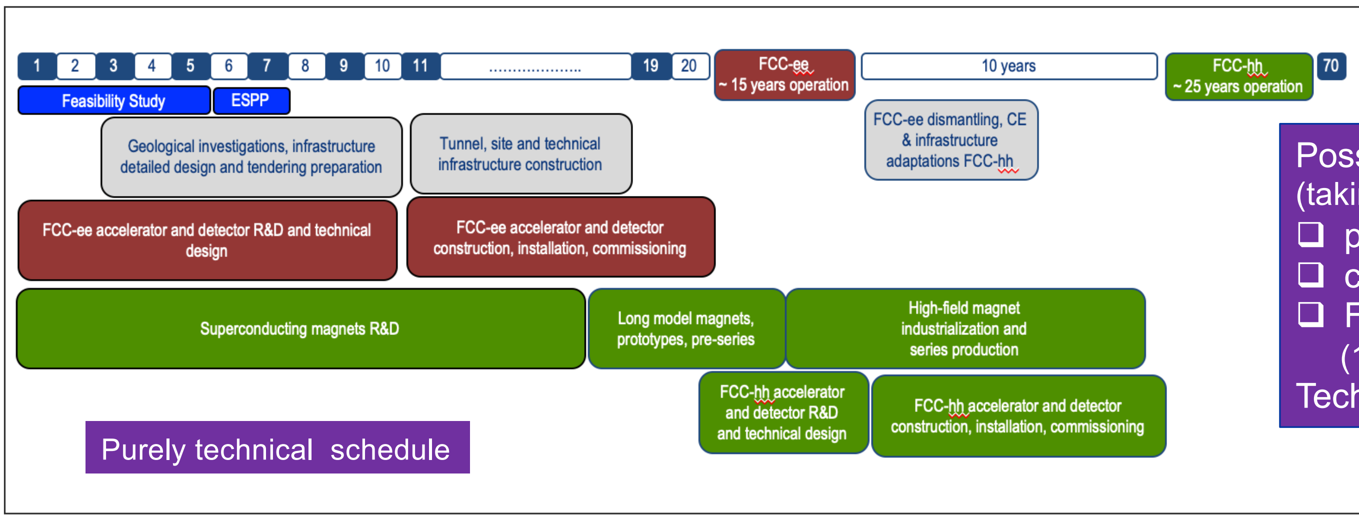
Numbers are for 100 km ring

	$\sqrt{s}$	L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV Z 160 WW 240 H ~365 top	230 $\times 10^{34}$ 28 8.5 1.5	75 5 2.5 0.8	2-4 experiments Total ~ 15 years of operation
pp **FCC-hh**	100 TeV	5 $\times 10^{34}$ 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

Potentially a multi-stage facility with immense physics potential (energy and intensity).

Feasibility Study:

- ❑ Focus is on FCC-ee and magnet R&D
- ❑ ~ 40 MCHF/year from CERN budget (half for magnet R&D)
  Additional funding from EU and collaborating institutes (e.g. CHART)
- ❑ Results will be summarised in Feasibility Study Report end 2025



Possible schedule
(taking into account resources constraints):

- ❑ project's approval by end of decade
- ❑ construction's start early 2030s
- ❑ FCC-ee operation: 2048-2063
  (10 years Z, W, H and 5 years tt)

Technical schedule: operation starts early 2040s

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 to identify and remove any showstopper
- ❑ 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)
- ❑ Identification of substantial resources from outside CERN's budget for the implementation of the first stage project (tunnel and FCC-ee)
- ❑ Consolidation of the physics case and detector concepts (in particular FCC-ee detector requirements and technologies)

- ❑ FCC Collaboration: 147 Institutes (12 from US) from 34 countries
- ❑ Plenty of opportunities for interesting work (new detector concepts, accelerator technologies, environmental impact and sustainability, etc.)
  → more collaborators from the US would be very much welcome!

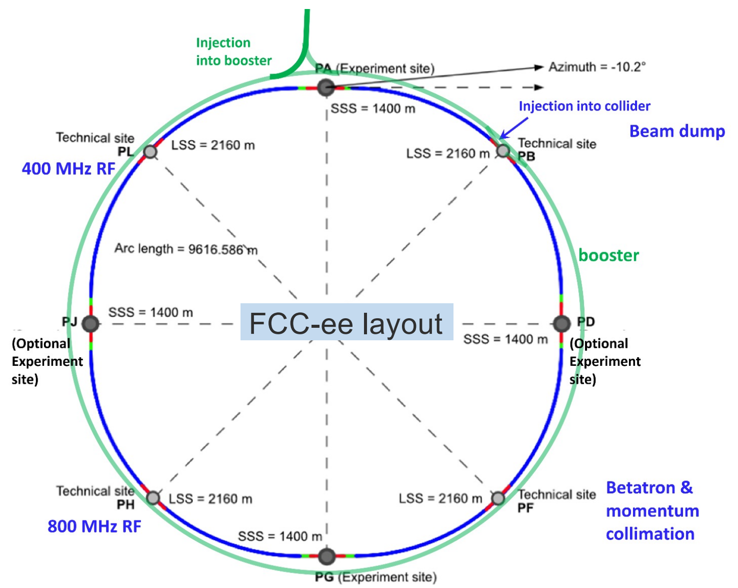
FCC Feasibility Study 2021-2025

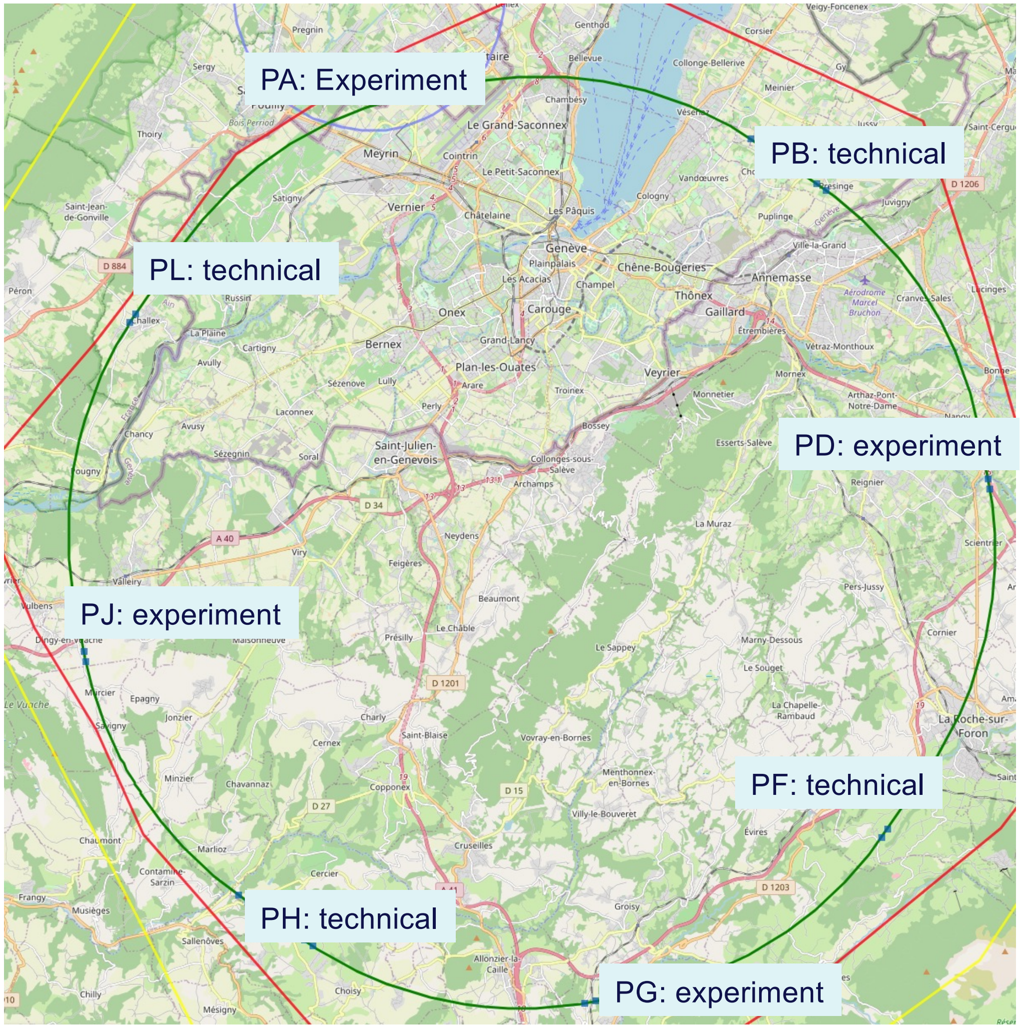
Major recent milestone: optimization of ring placement.

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: 91.1 km ring, 8 surface points

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





CLIC and muon colliders goals 2021-2025

CLIC goals:

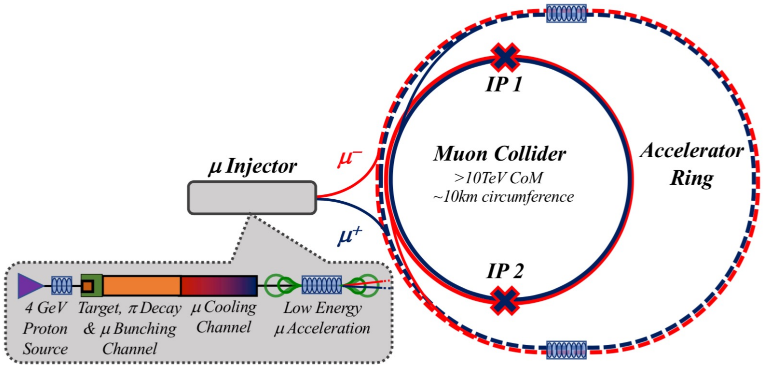
- ❑ finalise X-band technology towards construction readiness (accelerating structure's conditioning and manufacturing)
- ❑ improve power efficiency (e.g. klystrons)
- ❑ optimise luminosity for first-stage machine (beam dynamic studies, machine alignment and stability, etc.)
- → "**Project Readiness Report**" by end 2025 (as input to next ESPP)

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

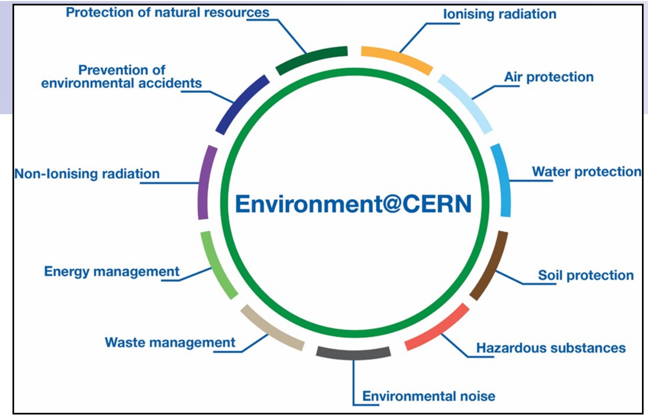
Muon collider's goals: work on main challenges, including muon source and cooling, fast-ramping magnets, accelerator and collider rings, neutrino background and civil engineering

→ determine by end 2025 (as input to next ESPP) if **investment in muon collider test facility** and CDR **is justified** from a scientific perspective.

Study initially hosted by CERN; CERN resources allocated.



Environment and sustainability



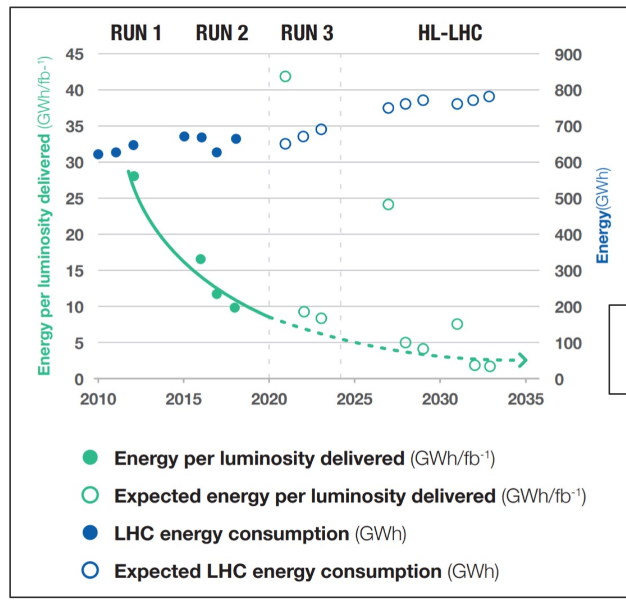
2 public Environment Reports released: https://hse.cern/environment-report
Describe current status for 11 domains and set goals to minimise CERN's impact on environment (e.g. reduction of emissions by 28% by 2024, compared to 2018)

> 70 MCHF investment from CERN's budget on environmental projects over 2016-2026

3 projects underway to recover waste energy from CERN infrastructure (LHC cooling towers, new Data Centre in Prévessin) and heat CERN sites and nearby village in France
→ energy savings/re-use and reduction of emissions.

Energy recovery from LHC Point 8 to heat a new residential village in the town of Ferney-Voltaire, France (~ 8000 people)

Significant improvement with time in scientific performance (→ physics output) for ~ same amount of electricity consumption



Run 2: ~ 10 GWh/fb^{-1}
HL-LHC : ~ 2.5 GWh/fb^{-1}

Conclusions

CERN has a compelling and broad scientific programme:

- ❑ LHC will be operating at the E-frontier until ~ 2042
- ❑ facilities and experiments at injectors, complementary to the collider, serving a broad community (including neutrinos)
- ❑ vigorous R&D and design studies for future facilities

The 2020 ESPP has identified the Future Circular Collider as the preferred option for a future post-LHC collider at CERN.
Immense physics potential, but also a very challenging and ambitious project.
Feasibility Study started and will be completed at the end of 2025. Substantial resources allocated.
Focus is on FCC-ee and magnet R&D.
Alternative options being pursued as well

To maintain interest in CERN and motivate the community (esp. the young people!), it is crucial to:

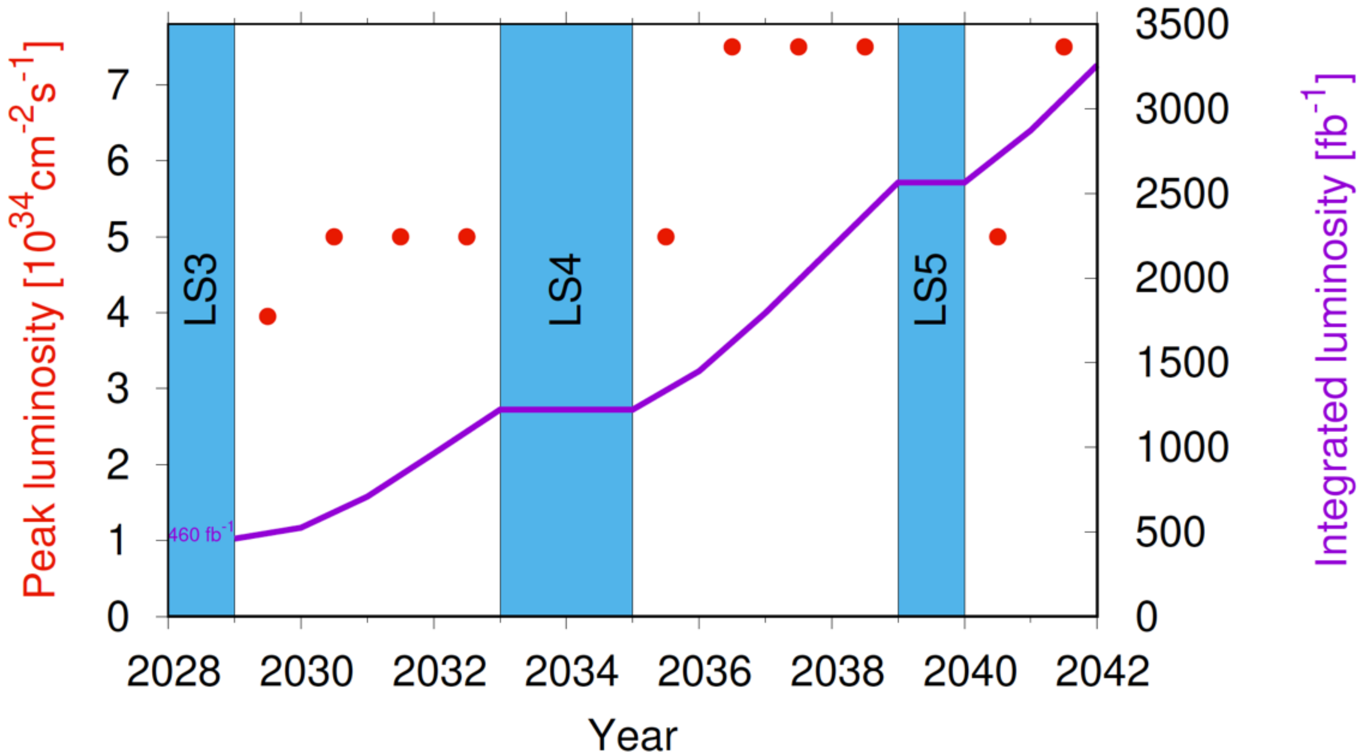
- ❑ avoid too-long gap between end of HL-LHC in ~ 2042 and beginning of physics at a new facility (hopefully mid-2040s)
- ❑ build new facility in parallel to HL-HLC operation → young people can work on HL-LHC data analysis and R&D for or construction of new facility

The contributions of DOE, NSF and US scientists (~17% of CERN's users), in particular intellectual contributions of the young scientists, have been crucial to the success of the LHC and CERN more generally.
They will continue to be crucial also in the future: in particular, FCC will only be possible with the strong participation of the US (ideas, technologies, resources).

Likewise, CERN is committed to support LBNF/DUNE and open to discuss collaboration on future projects in the US.

So many intriguing questions in particle physics and so many nice opportunities to address them
→ global, worldwide coordination and collaboration are needed to cover all of them … the future of the field is BRIGHT!

EXTRAs



Peak luminosity [10^{34}cm^{-2}s^{-1}]
Integrated luminosity [fb^{-1}]
Year
LS3
LS4
LS5
460 fb^{-1}
0
1
2
3
4
5
6
7
0
500
1000
1500
2000
2500
3000
3500
2028
2030
2032
2034
2036
2038
2040
2042

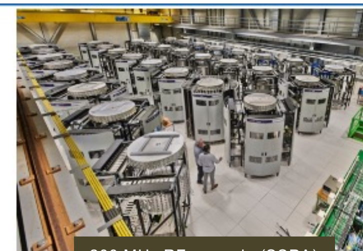
LHC Injectors Upgrade (LIU)

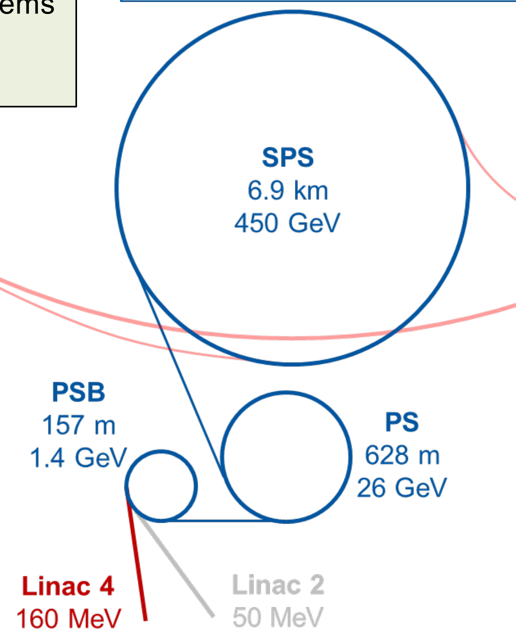
Provide beams of the intensity and brightness needed for HL-LHC:
2.3×10^{11} p/bunch, ε~ 2.1 μm
at LHC injection

Linac 4: 160 MeV H^-
PSB: 1.4→ 2 GeV
PS: new injection and feedback systems
SPS: new 200 MHz RF system

SPS upgrade

- **Main RF system upgrade** (new solid state power plants – 2 x 1.6 MW)
- **Impedance mitigation** to improve beam stability
- More robust **beam dump and protection devices**


200 MHz RF upgrade (SSPA)



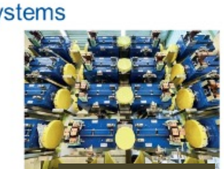
Linac 4, has been built to take over.

- Higher energy **160 MeV**
- Acceleration of **H^- ions** (charge exchange $H^- \rightarrow p^+$ in the PSB)

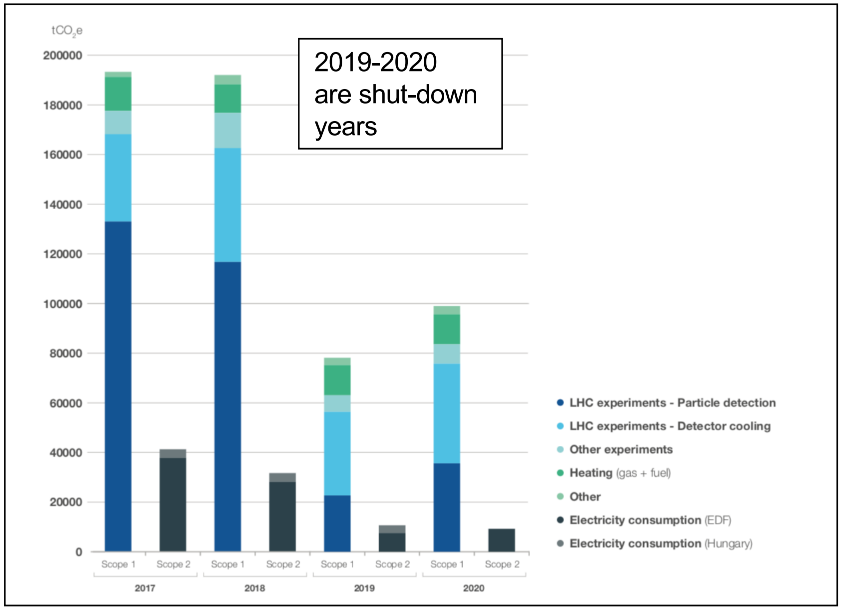
PSB upgrade

- **H^- charge exchange injection** at 160 MeV → improved beam brightness (weaker space charge forces)
- **Energy : 1.4 GeV → 2 GeV**
  - New main power supply
  - New RF systems

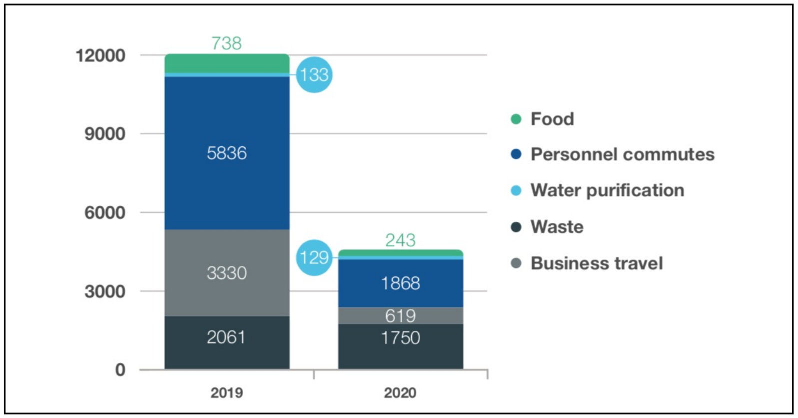

Finmet RF cavities


Injection system

CERN's 2nd Environment Report (public)



New in 2021 report: first assessment of Scope 3 emissions



Emission arising from procurement not included.
"Sustainable procurement project" started

Goal is to reduce emissions by 28% by 2024 (baseline 2018)