Regional Perspectives:

Europe

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University of Freiburg / Germany

2020 Update of the European Strategy for Particle Physics

The 2020 update of the **European Strategy for Particle Physics (ESPP)** has defined the major priorities

(i) Full exploitation of the LHC and the High-Luminosity LHC

(ii) An **electron−positron Higgs factory** is the highest−priority next collider

(iii) Longer term: the European particle physics community has the ambition to operate a **proton−proton collider at the highest achievable energy**

In addition: *A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics strategy (Dark Matter, exploration of flavour and fundamental symmetries)*
→ CERN "Physics Beyond Colliders" programme, complemented by other European Laboratories

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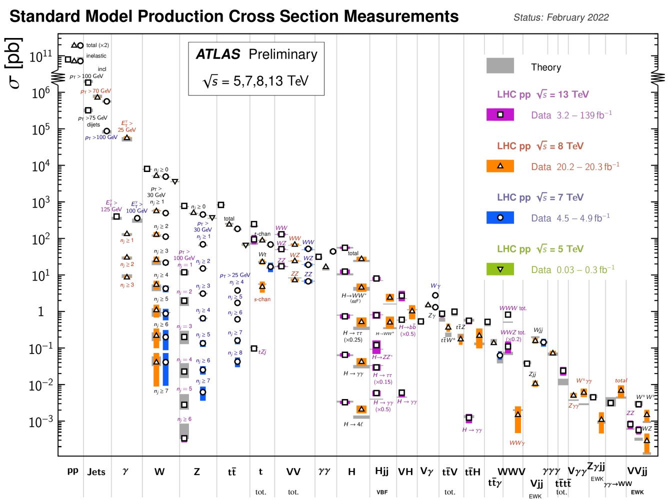
(iv) Ramp up of R&D effort focused on **advanced accelerator technologies, in particular for high-field superconducting magnets, including high-temperature superconductors**
→ Organised by the Lab Directors Group, an ***Accelerator R&D roadmap*** should be developed

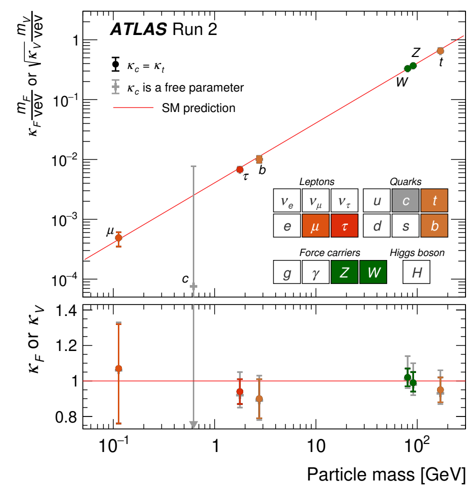
(v) Maintain a **strong focus on instrumentation**
→ *Organised by ECFA, a **Detector R&D Roadmap** should be developed*

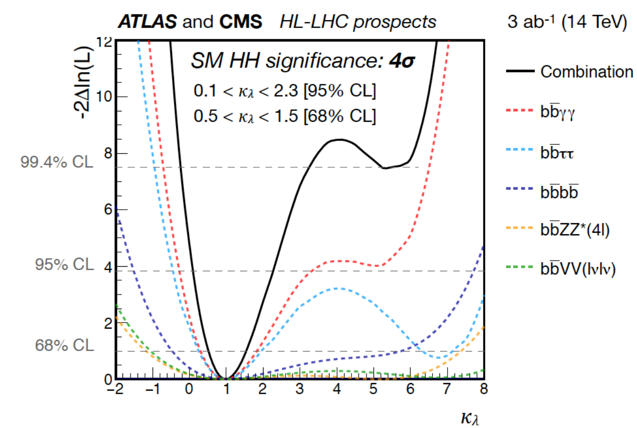
1. LHC and Upgrades for HL-LHC

- Excellent LHC operation and physics results from Run 1 and Run 2
- Run 3 (2022 – 2025) has started well (outstanding perf until mid July 2023, e.g. 1.2 fb^{-1} in 24 h), however, short pp run in 2023 (32 fb^{-1}) due to incidents: (power glitch → magnet quench and leaking bellow between cold mass and insulation vacuum)

  Despite this: good prospects for Run 3 (2024 – 2025)
- HL-LHC: First glimpse at Higgs-boson self coupling expected

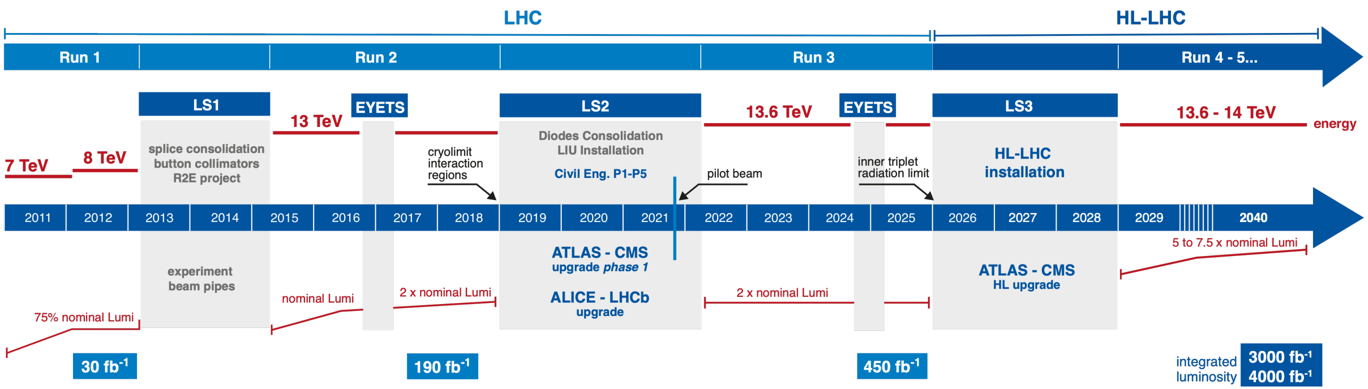






First sensitivity on the Higgs boson self coupling (±50% uncertainty)

Status of HL-LHC preparation

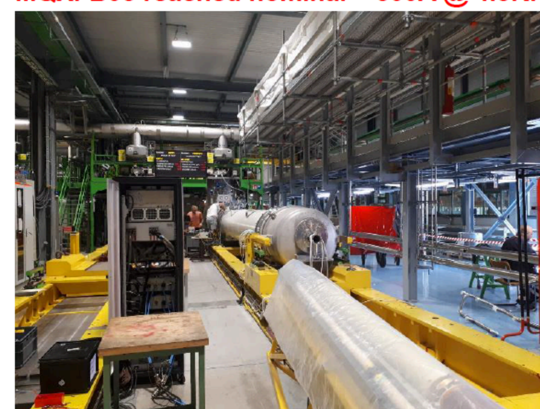


- Excellent progress on the machine side, on track for start of operation in 2029 (75% of resources committed)

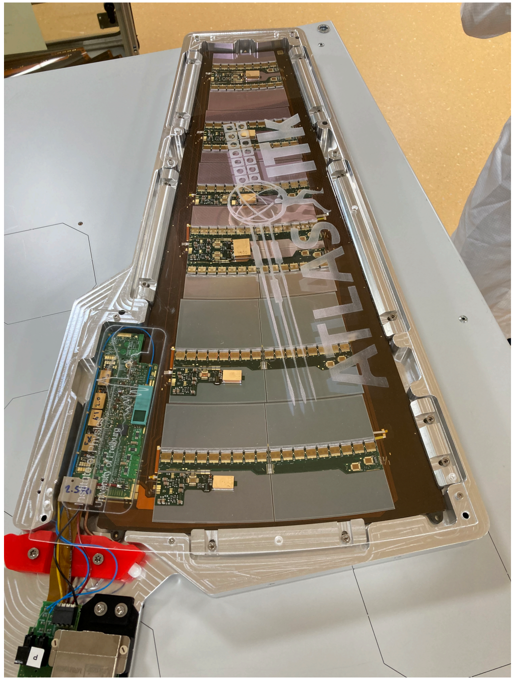
- Excellent progress on all key technologies;

- Encouraging news from both the US and CERN Nb_3Sn magnet programmes
  (on track for series production of Nb_3Sn HL-LHC inner triplet quadrupole magnets)

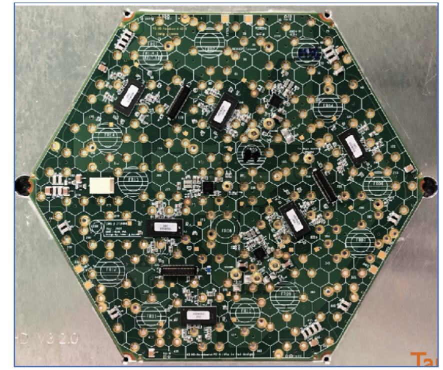
MQXFB03 reached nominal + 300A @ 4.5K!

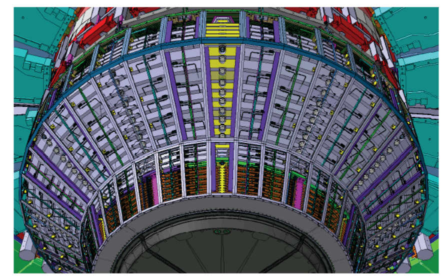


Status of Phase-II detector upgrades (ATLAS and CMS)

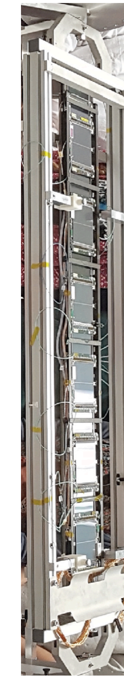


First fully functioning petal of the ATLAS ITk endcap





CMS HGCAL



First ladder fully equipped with 12 functional modules

- Projects are making very good progress (in transition to (pre)production)
- However, the schedule for both experiments remains tight
- Challenges also remain due to the worldwide political and economical situation

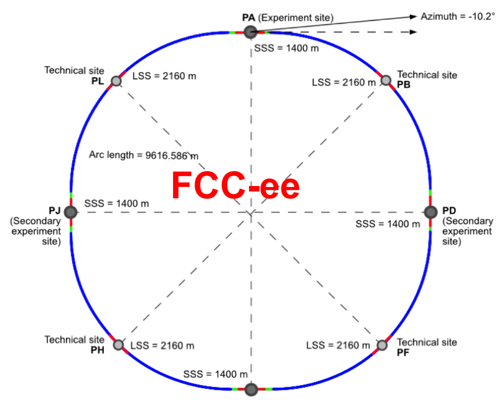
2. FCC: Future Circular Collider

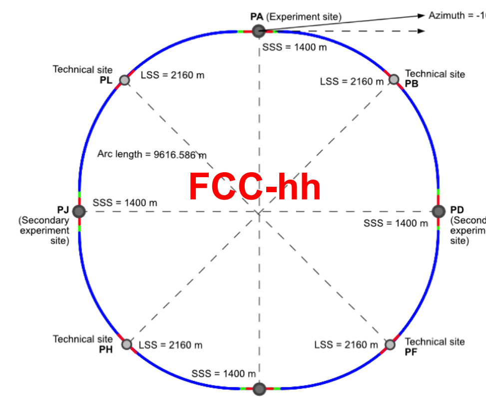
FCC integrated programme

Comprehensive long-term programme maximising physics opportunities:

- Stage 1: FCC-ee : e^+e^- Higgs, electroweak & top factory at highest luminosities [91 GeV → 365 GeV]
  Build on large progress made at circular e^+e^- colliders over the past decades → reach luminosities beyond 10^{34} cm^{-2} s^{-1}
- Stage 2: FCC-hh : 100 TeV pp collider, energy frontier machine (in addition: eh and ion options)

- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC project start is coupled to HL-LHC programme → start operation of FCC-ee around 2048;
  can be accelerated if more resources available





2029 - 2041	2048 - 2063	2074 -

FCC Feasibility Study

"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****."*

- A Feasibility Study (FS) and its organisational structure have been approved by CERN Council in June 2021
- Report to be released by end of 2025
  → Basis for a decision at the next Strategy Meeting expected in 2026/27

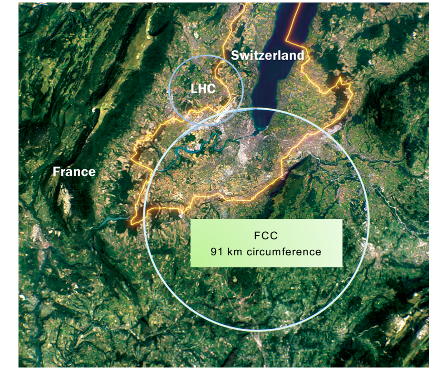
  Mid-term report by end of 2023: all documents have been submitted, review ongoing

Mid-term review ***setup and deliverables defined*** *in CERN/SPC/1183/Rev.2:*

- *The scientific and technical results be reviewed by the* ***Scientific Advisory Committee***
- *The cost and financial feasibility, which will focus on the first-stage project (tunnel, technical infrastructure, FCC-ee machine and injectors), be reviewed by a* ***Cost Review Committee*** *including external experts.*

Both Committees have submitted their report → Discussion in CERN Council

FCC Feasibility Study



- Demonstration of the **geological, technical, environmental and administrative feasibility** of the **tunnel and surface areas** and optimisation of the **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 colliders 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.
- **Identification of substantial resources from outside CERN's Budget** for the implementation of the first stage of a possible future project (tunnel and FCC-ee).
- Consolidation of the **physics case** and **detector concepts** and technologies **for both colliders**.

Feasibility Study funded from CERN budget: 100 MCHF total over 5 years; in addition: ~ 20 MCHF/year for high-field magnet R&D; Additional funding from the European Commission and collaborating institutes (e.g. CHART collaboration with Switzerland)

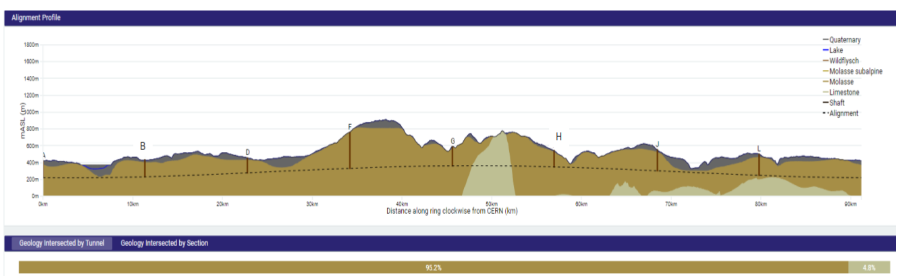
Optimised FCC layout (used for further feasibility studies)

- Layout converged on an optimised placement, chosen out of ~ 100 initial variants;

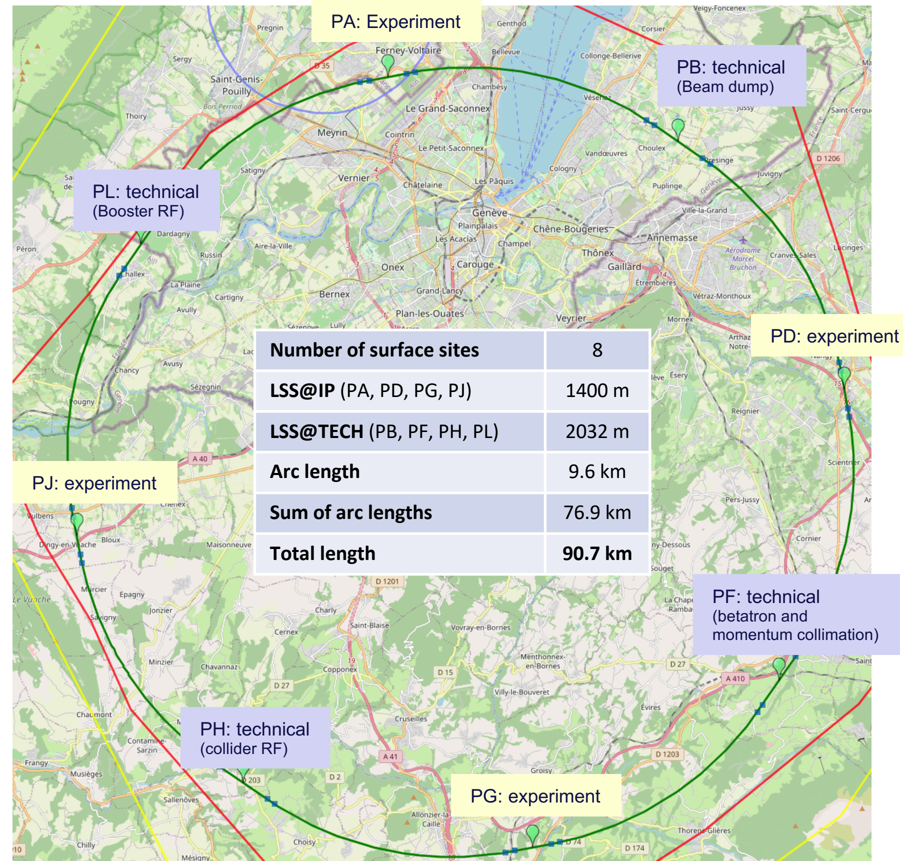
(based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine perf.** etc.)

- 90.7 km ring, 4-fold symmetry
  8 surface points, 2 - 4 experiments

Whole project now adapted to this placement



95% in molasse geology → minimising tunnel construction risk

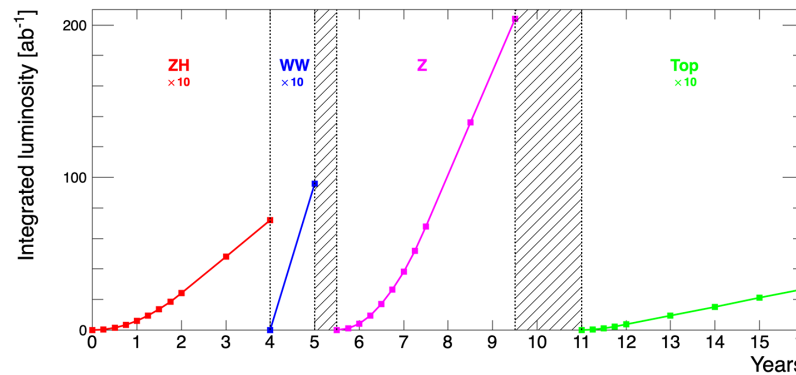


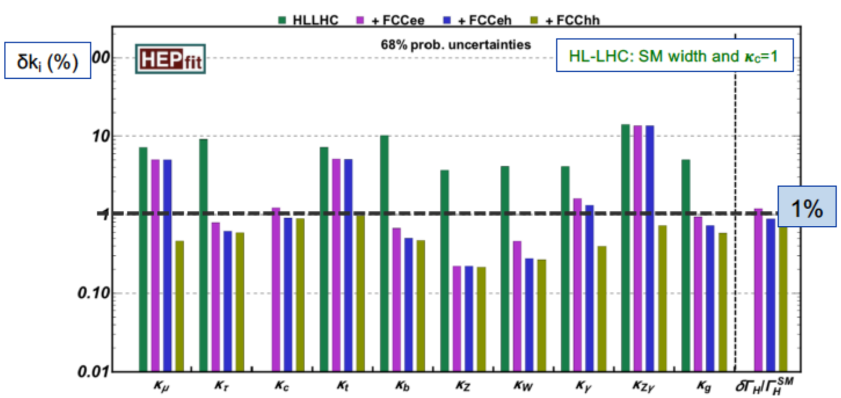
Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 km
Total length	**90.7 km**

FCC physics plans and 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	5-30 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 possible FCC-ee running scenario





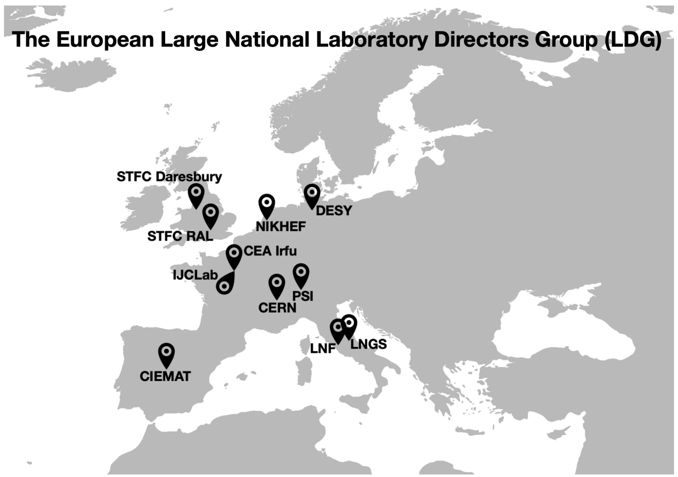
A multi-stage facility with enormous physics potential:

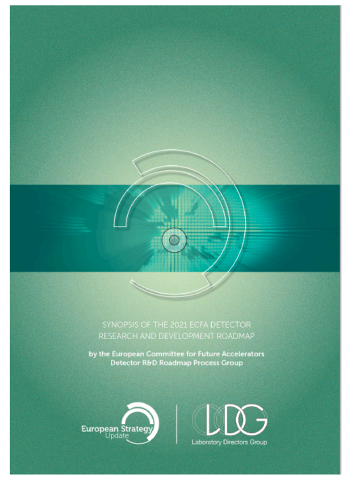
FCC-ee:
- Significant improvement in Higgs couplings
- Huge electroweak potential
  (δm_Z ~ 100 keV, $\delta\Gamma_Z$ ~ 25 keV, δm_W < 500 keV, δm_t ~45 MeV)
- Large potential in flavour physics

FCC-hh:
- Energy frontier machine (x10 LHC)
- Ultimate Higgs precision
- Also provides heavy-ion collisions and, possibly, ep / e-ion collisions

3. Accelerator R&D Roadmap

"The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, … Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes."





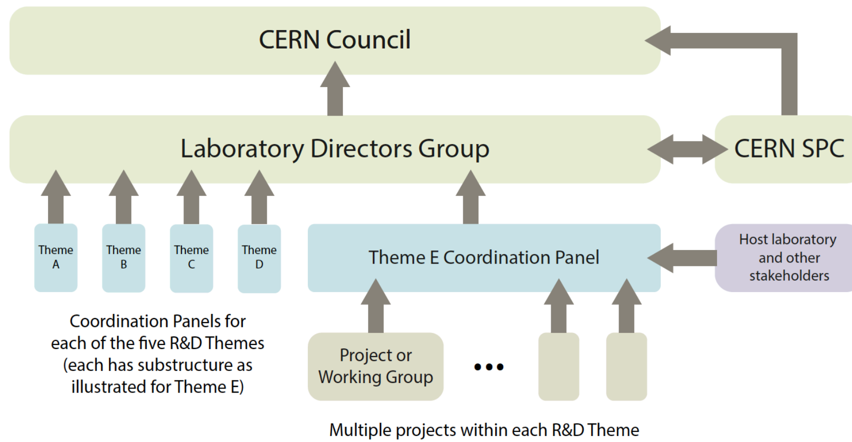
Key questions addressed:

- *What R&D remains to be done towards future facilities?*
- *What are the priorities?*
- *How long might it take? How much will it cost?*
- *What different options and trade-offs exist?*
- *What are the dependencies or conflicts between activities?*

Goal: provide the evidence allowing future decision-making by the field

https://arxiv.org/abs/2201.07895

Implementation: Coordination Structure of the Accelerator R&D



- Structure for cooperative, coordinated and focussed R&D towards future machines set up;

  Strong involvement of European National Laboratories and other institutes

- Coordination panels formed, work started

Coordination panel chairs
Magnets: M. Lamont (CERN), P. Vedrine (IRFU)
RF: G. Bisoffi (INFN-LNL), Peter McIntosch (RAL)
Plasma: W. Leemans (DESY), Rajeev Patahill (RAL)
ERL: J. D'Hondt (Brussels), M. Klein (Liverpool)
Muons: S. Stapnes (Oslo), D. Schulte (CERN)

Focus on five R&D Themes:

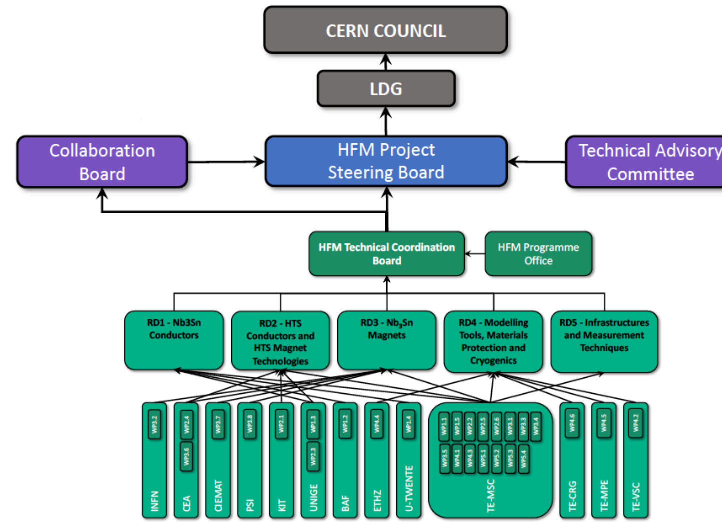
- High field magnets
- RF structures
- Plasma / Laser acceleration
- Energy-recovery Linacs
- Muon Beams

High-field Superconducting Magnets

- Key technology for future accelerators (hadron colliders, muon colliders, neutrino beams, …)
- To reach the required field strength of 16 – 20 T for FCC-hh, new technologies have to be **established and brought into industrial production**
  (Present candidates: Nb_3Sn and High-Temperature Superconductors (HTS), …)

Accelerator Roadmap:

- Encompass Nb_3Sn and HTS (REBCO, …) developments
  - Demonstrate **Nb_3Sn** magnet technology for large-scale deployment
  - Demonstrate the suitability of HTS for accelerator magnet applications
- "Vertically integrated" approach to R&D
  - Development of all aspects from conductors to cables to magnets to systems
  - Emphases: full system optimisation, fast turnaround for R&D



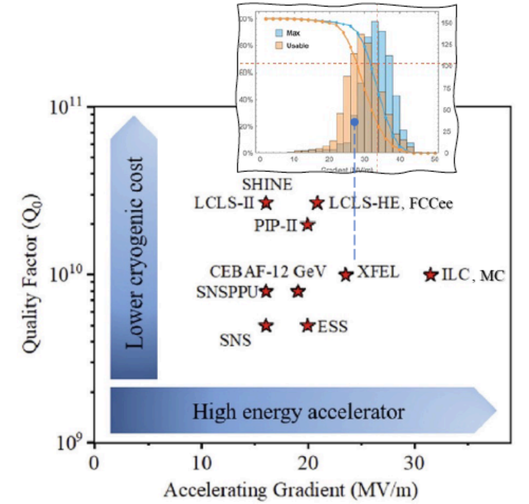
Other Accelerator R&D areas

RF Structures:

- Overall goal: optimisation of RF structures and quality;
  beneficial for many projects

Working groups: Bulk Nb, thin films, couplers, NC high gradients,
RF power sources, low level RF (control), ..

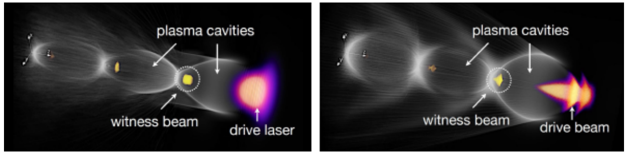
[CERN, CEA-F, CNRS-F, INFN-I, Helmholtz-D, STFC-UK, …]

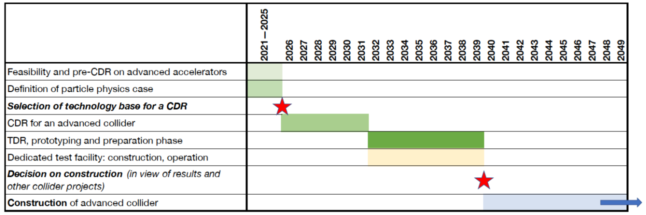


Plasma / Laser acceleration:

- Panel proposes a plasma and laser accelerator R&D roadmap that should be implemented and delivered in a three pillar approach

By next strategy: A feasibility and pre-conceptual design report, i.e. evaluate the potential and performance reach for colliders





- *"The recently proposed HALHF concept may act as a spur to the improvement of specific plasma-acceleration techniques"*
  B. Foster et al. New J. Phys. 25 (2023) 093037, [arxiv:2303.10150]
  but: *"HALHF cannot be built tomorrow: many unsolved problems remain."*

[DESY-D, INFN-I, STFC-UK, …]

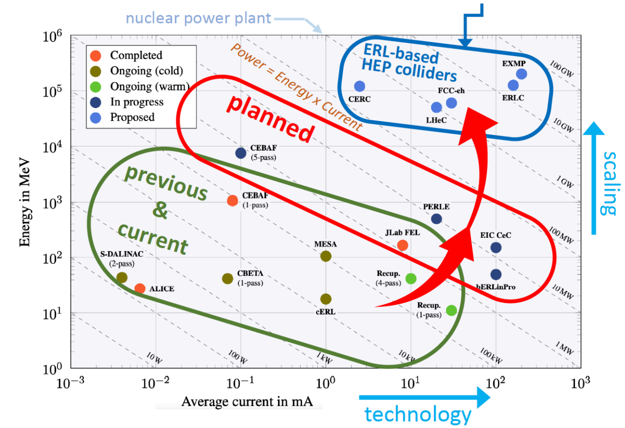
Other Accelerator R&D areas

Energy-Recovery Linacs:

- Principles or ERLs have been successfully demonstrated
  → reduced power consumption, high injector brightness,
  beam dump at injection energy

- Focussed technical R&D into key technologies to develop or upgrade European facilities for the mid-2020s (e.g. **PERLE at IJCLab**)
  (high-current electron sources, high-power superconducting RF technology, …)

[CNRS-F, Helmholtz-D, …]



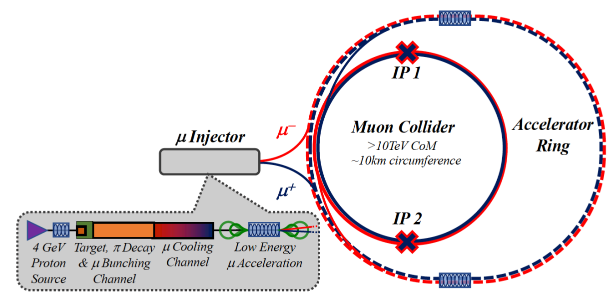
Programme is relevant to both absolute performance and sustainability of future machines

Muon Beams:

- Potentially interesting path to realise high-energy lepton colliders, however, the technology must overcome several significant challenges

- **Roadmap Objectives**: again focussed on the “plausibility case”
  → Examine the key technical barriers and cost drivers before the next strategy
  → Develop muon-collider concept (focus on 10 TeV, with 3 TeV as potential initial stage → assessment report by 2026

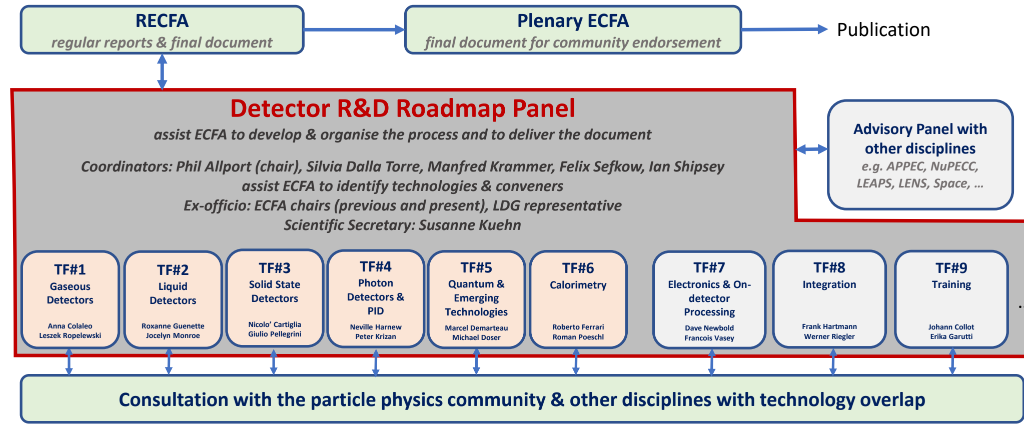
[CERN, INFN-I, STFC-UK, CEA-F, …]



4. Detector R&D Roadmap

https://cds.cern.ch/record/2784893

- *As suggested by the 2020 ESPP, a Roadmap for Detector R&D has been developed; Released at the end of 2021*
- *Work was organised by a Detector R&D Roadmap Panel (ECFA)*



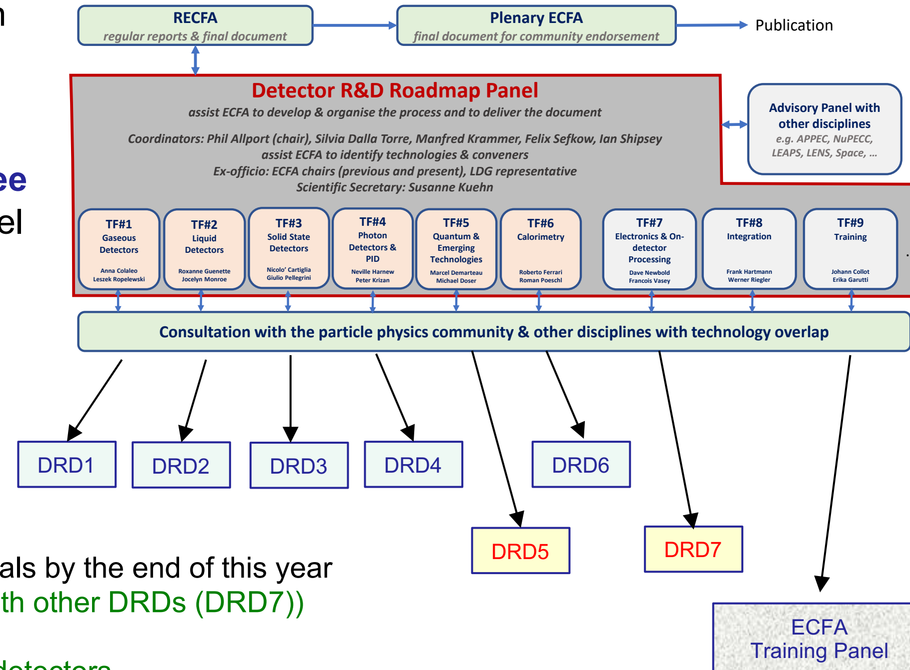
- ***Task forces*** *were composed of experts from the community covering key sub-topics in the relevant technology areas; followed by full community involvement, bottom-up approach*
- *Implementation defined throughout 2022*

Detector R&D Roadmap

- The implementation of the roadmap foresees the formation of Detector R&D Collaborations (DRDs) at CERN;

- Five proposals have been submitted and are under review by the newly established **Detector R&D Committee (DRDC)** at CERN with support by the ECFA Detector Panel

  - DRD1: gaseous detectors
  - DRD2: liquid detectors
  - DRD3: solid state detectors
  - DRD4: particle identification and photon detection
  - DRD6: calorimeters



DRD5 (quantum, emerging technologies) and
DRD7 (electronics, transversal activity, LoI exists) will submit proposals by the end of this year (later timescale due to: internal coordination (DRD5), coordination with other DRDs (DRD7))

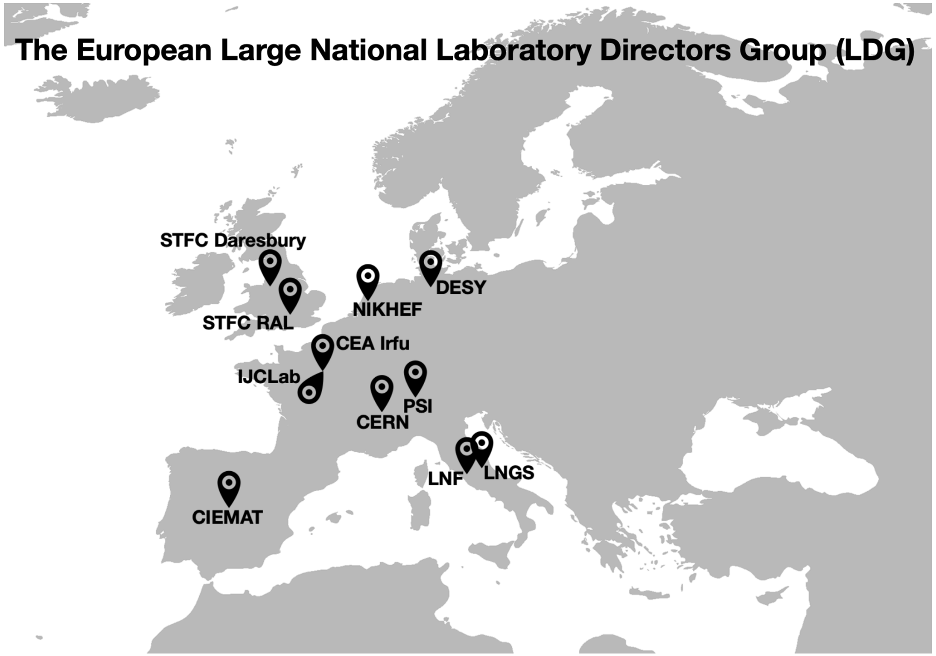
DRD8 will probably follow later, focussing on mechanics of tracking detectors

- Collaborations are open for world-wide collaboration; participation from outside Europe is very welcome!

- First decisions on approval expected in Dec. 2023 (CERN Research Board), for startup in Jan. 2024

- MoUs to follow in 2024, funding agency involvement via RRB-like structure

5. Activities in European Laboratories (beyond CERN)



All European Laboratories are strongly engaged in the described activities and complement and support CERN

- Accelerator R&D
- Detector construction for HL-LHC and other experiments
- Detector R&D
- Physics exploitation

In addition, they carry out their **own, complementary Physics Programme**

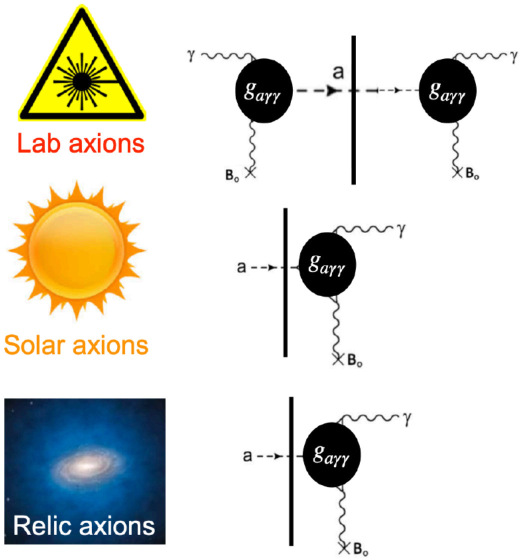
→ A few examples → next slides

DESY (Germany)

Axion Experiments at DESY

Complementarity and model dependencies

Source **Detection**



Light-shining-through-a-wall and solar axion searches will reach sensitivities beyond present-day astrophysics limits with unique discovery potentials independent of cosmological assumptions

Frascati (LNF, Italy)

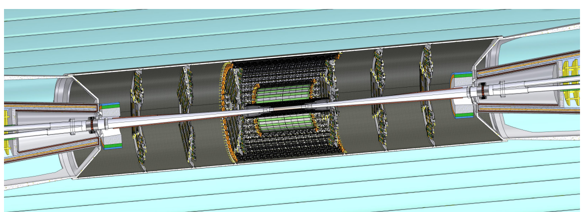
- Running two accelerator facilities:

  - The **DAΦNE** e^+e^- collider (1 GeV c.m.) with the annex Beam Test Facility (BTF)

  - The **SPARC_LAB** linear accelerator complex devoted mainly to plasma acceleration studies

- Headquarter of **European initiative EuPRAXIA** (beam-driven plasma acceleration → new accelerator complex**)**

- **FCC-ee Interaction region design**



- **KLOE detector → Fermilab** (near detector for DUNE)

PSI (Switzerland)

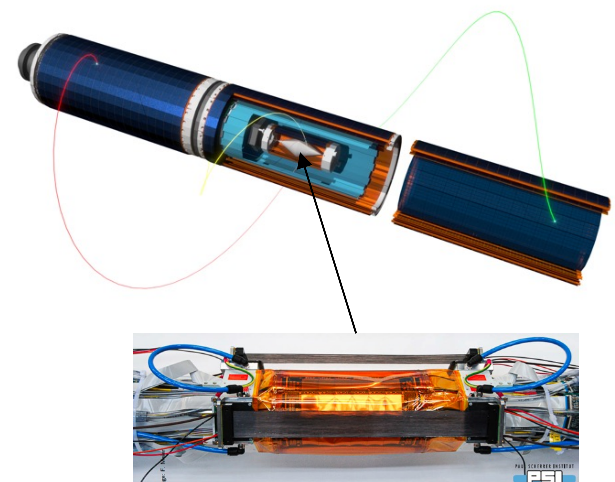
- Strong participation in **magnet R&D programme**

- Dedicated **Lepton-flavour violations** experiments

  e.g. MEG II**:** $\mu \rightarrow e\gamma$ ($< 3.1\ 10^{-13}$)

  Mu3e: $\mu^+ \rightarrow e^+e^-e^+$

  Sensitivity: ~ 10^{-15} (~ factor 500 improvement)



Pixel detector with 0.1 X_0 per layer,
50 μm HVMAPS sensors

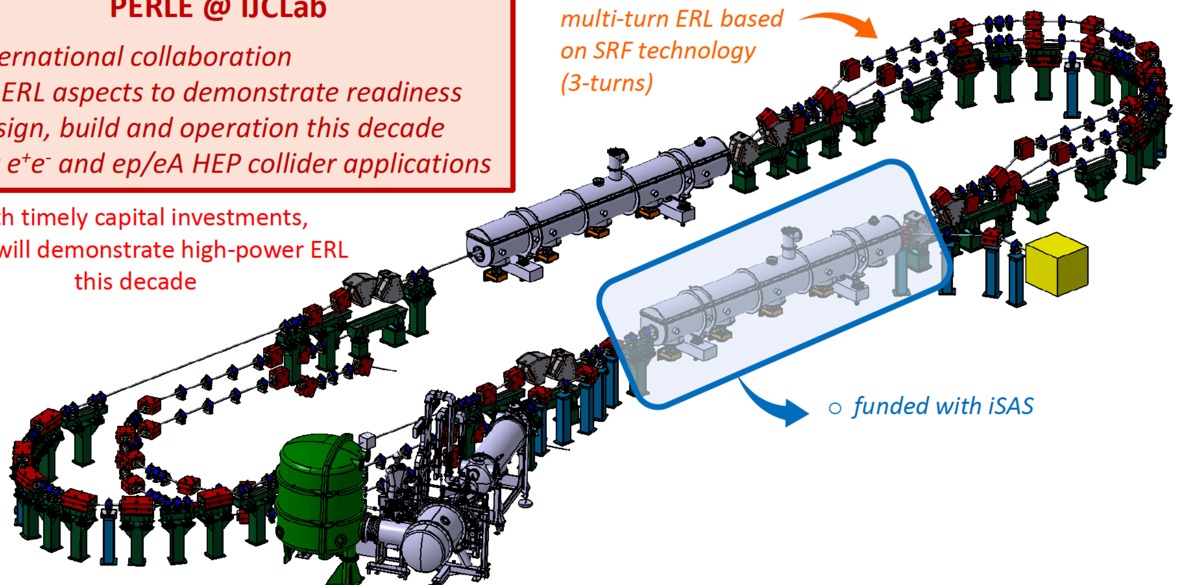
IJCLab (France)

Upcoming facilities for Energy Recovery Linac R&D

PERLE @ IJCLab

- *international collaboration*
- *all ERL aspects to demonstrate readiness*
- *design, build and operation this decade*
- *for e^+e^- and ep/eA HEP collider applications*

With timely capital investments,
PERLE will demonstrate high-power ERL
this decade



PERLE – Powerful Energy Recovery Linac for Experiments [CDR: *J.Phys.G* 45 (2018) 6, 065003]

Summary

- With the LHC and the HL-LHC programme, Europe has an ongoing unique physics programme at CERN

- To prepare for the future ambition of operating a Higgs factory, followed by a hadron collider of about 100 TeV, CERN has launched a feasibility study for the FCC

  - Mid term report submitted, under review

  - Very significant progress on many areas

  FCC-ee technology is mature, construction can proceed in parallel to HL-LHC operation and physics can start a few years after the end of the HL-LHC operation;

  FCC-hh will reuse same civil engineering and large part of FCC-ee technical infrastructure
  → optimisation of overall investment

- Europe has set up intensive R&D programmes for accelerator and detector R&D

- Both programmes, as well as the (HL)LHC and FCC programmes, are strongly supported by the National Laboratories in the European countries