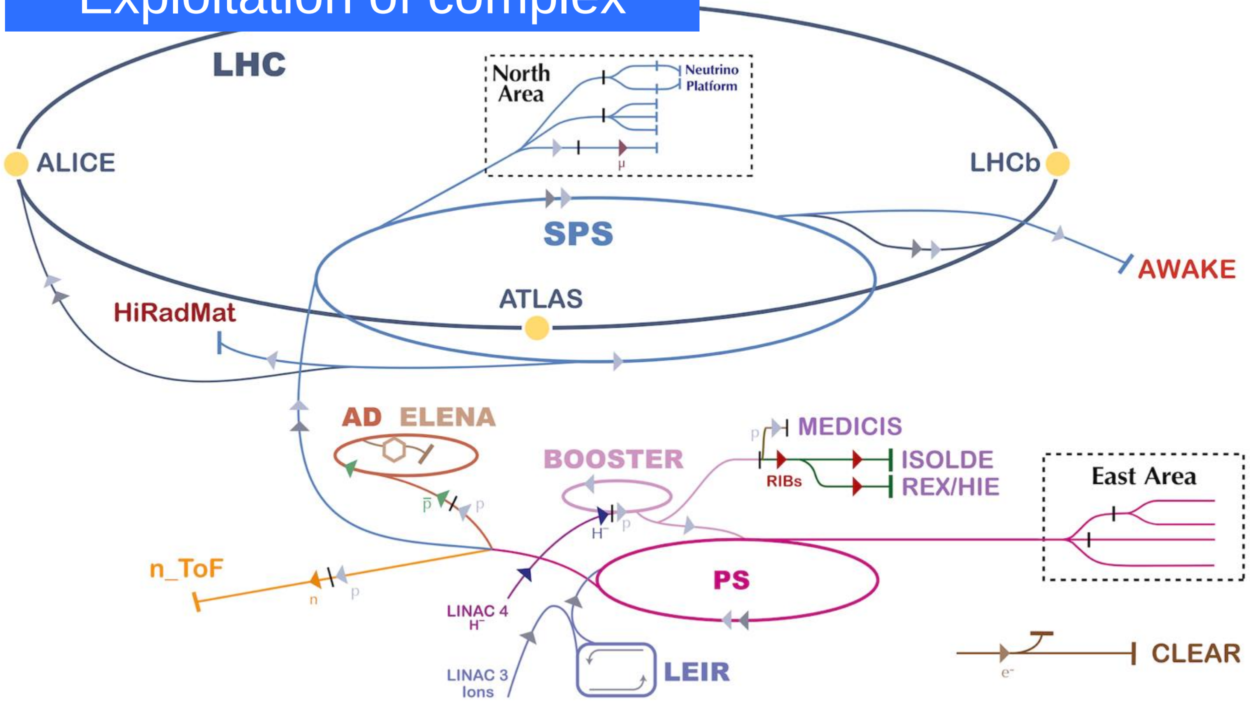
CERN’s future programme

Mike Lamont
IOP Joint APP, HEPP and NP Annual Conference 2024
11th April 2024

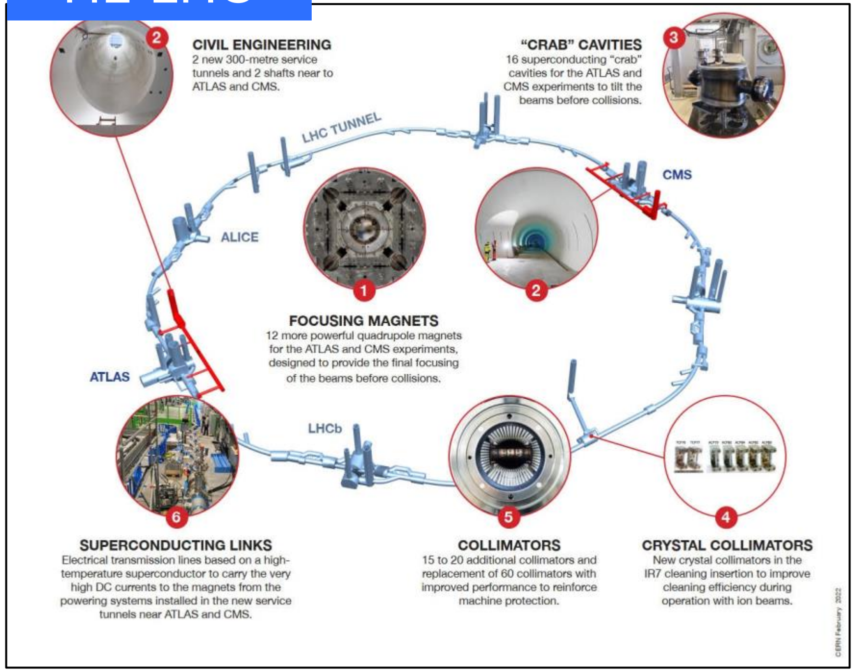
Our goal is to understand the most fundamental particles and laws of the universe.

Four pillars underpin CERN’s mission

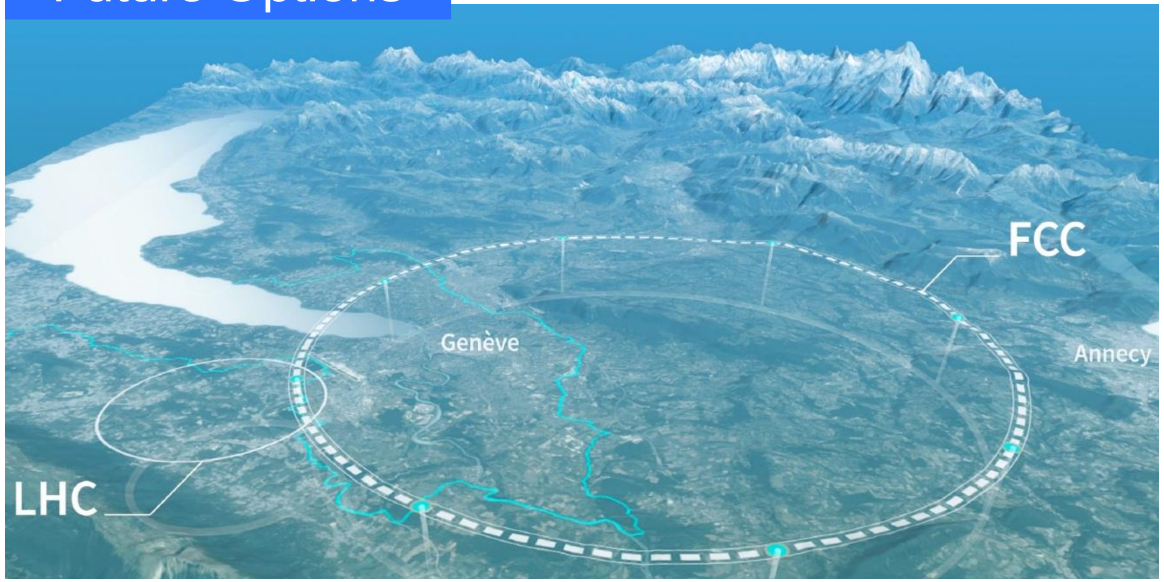
Exploitation of complex



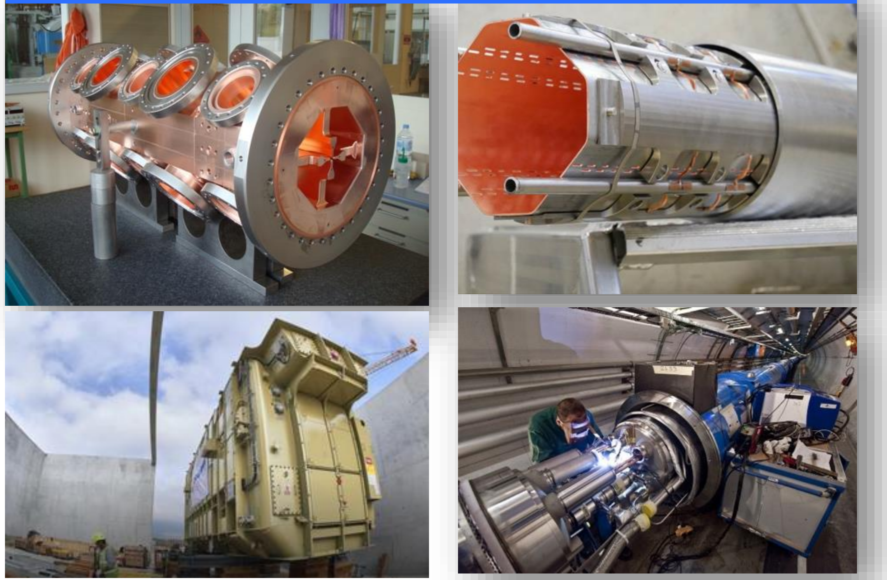
HL-LHC



Future Options



Technology/Engineering/R&D



CERN’s scientific strategy and programme based on 3 pillars

Full exploitation of the LHC:

- Successful Run 3: $\sqrt{s}$ =13.6 TeV
- High-Luminosity LHC upgrade (construction well advanced) - starts in 2029 ends ~2041

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)
- Future opportunities fostered within “Physics Beyond Colliders” study group

Preparation of CERN’s future:

- Intense accelerator R&D programme
- Future Circular Collider (FCC) Feasibility Study - final report in 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 recently confirmed for 2024-2026

European Strategy for Particle Physics 2020 Update

The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques.

The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.

2022 Snowmass Energy Frontier Summary

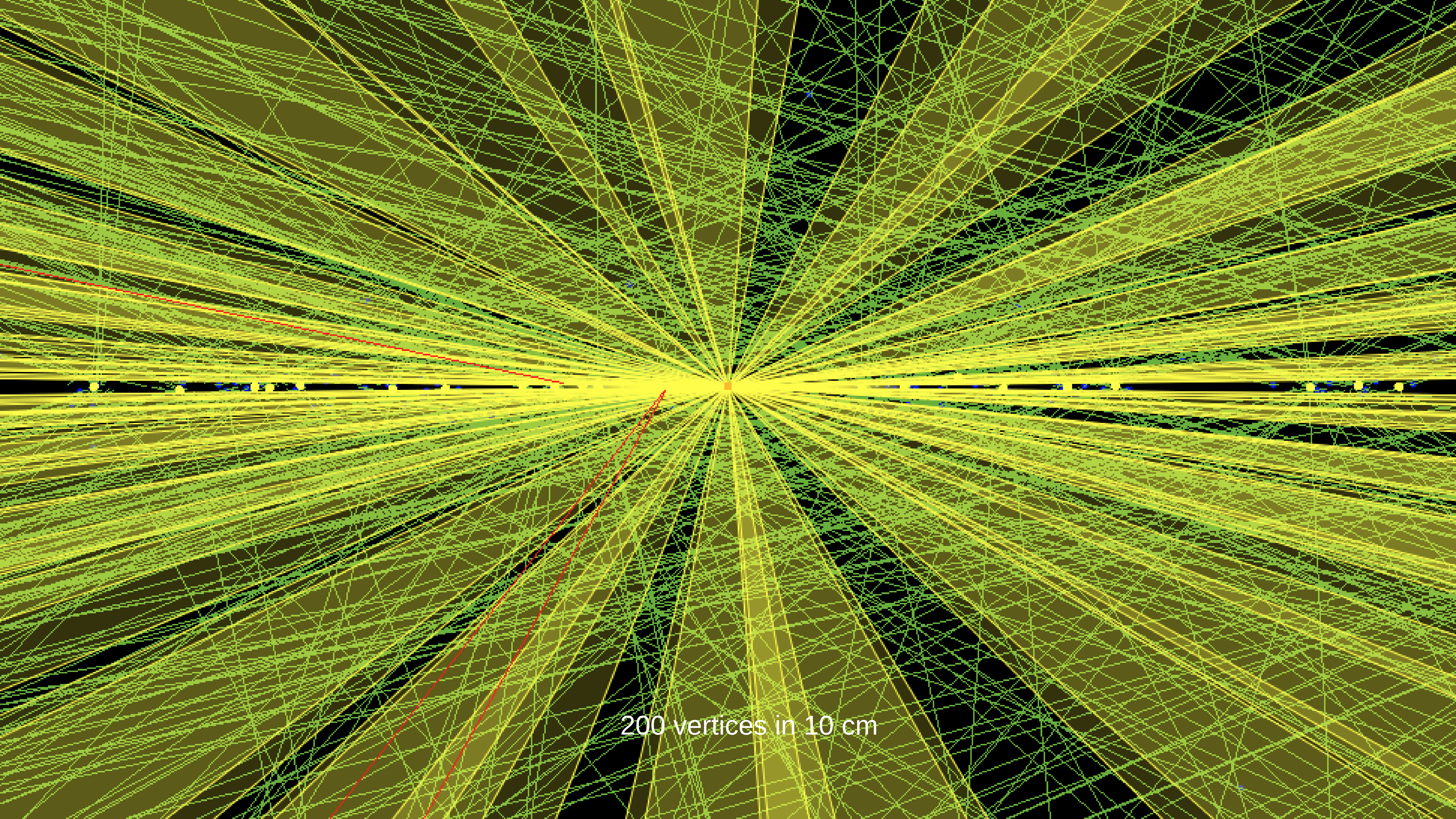
Our highest immediate priority accelerator and project is the HL-LHC, the successful completion of the detector upgrades, operations of the detectors at the HL-LHC, data taking and analysis, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.

HL-LHC - goals

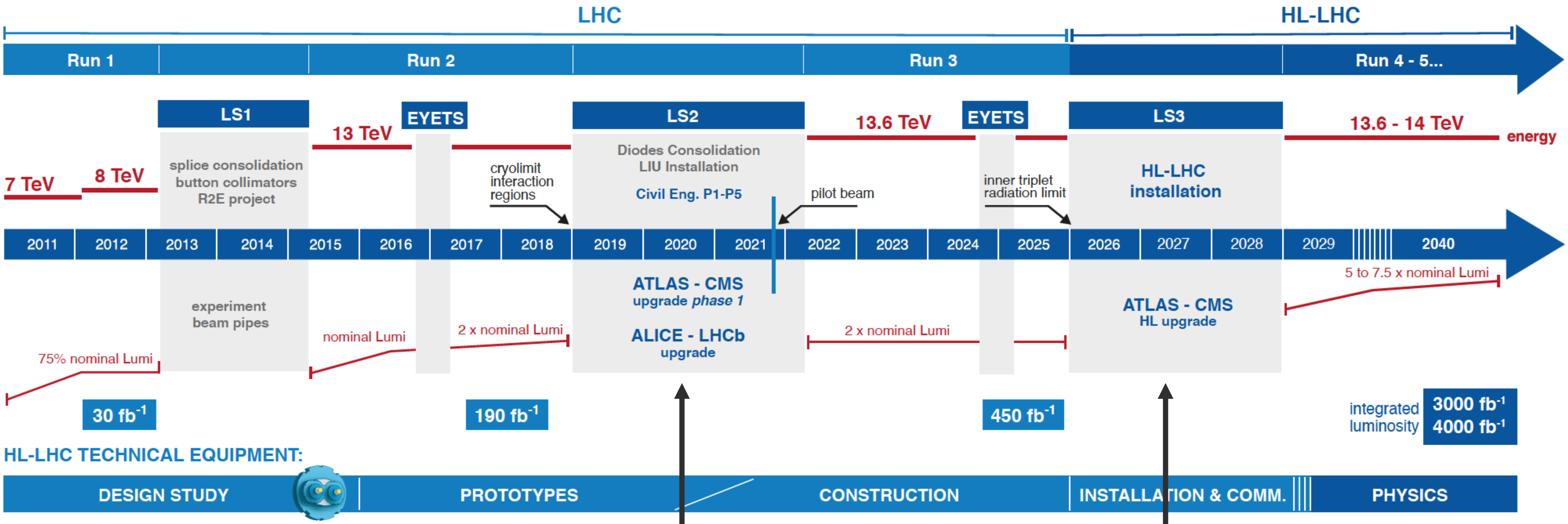
Prepare the machine for operation beyond 2025 and up to ~2040

Operation scenarios for:

- Total integrated luminosity of **3000 fb^{-1}** in around 10-12 years
- An integrated luminosity of **~250 fb^{-1} per year**
- **Nominal:** levelled luminosity of $5 \times 10^{34}\ cm^{-2}s^{-1}$ (events/crossing ~130)
- **Ultimate:** levelled luminosity of $7.5 \times 10^{34}\ cm^{-2}s^{-1}$ (events/crossing ~200)

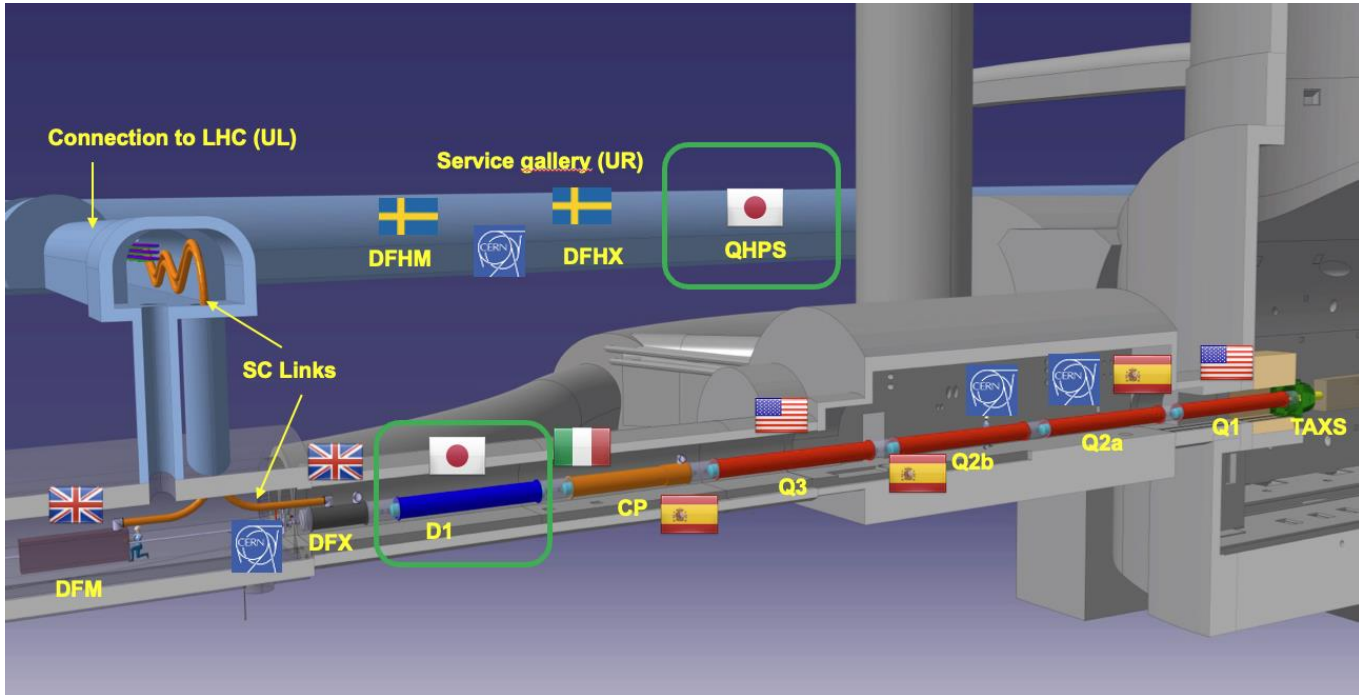

200 vertices in 10 cm

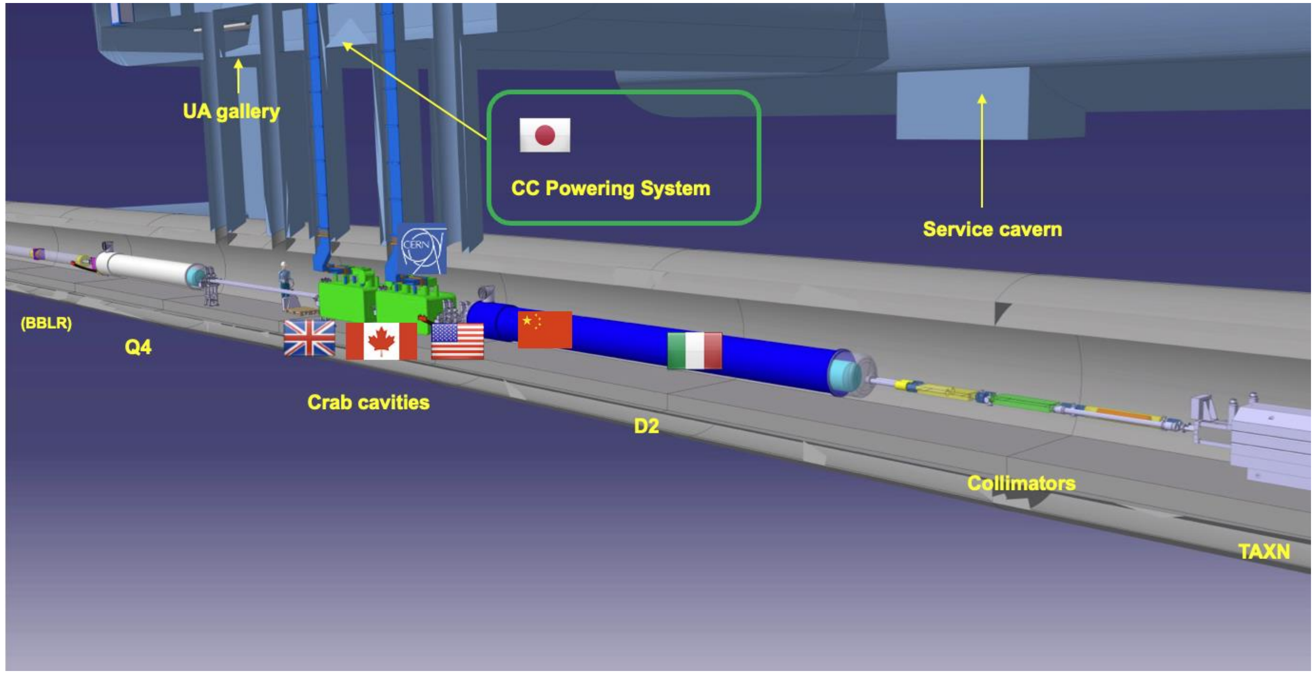
High Luminosity LHC (HL-LHC)

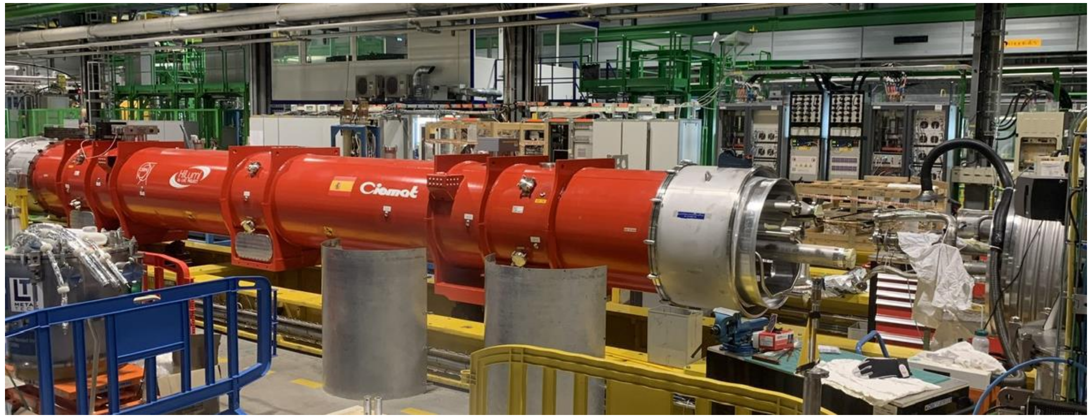


LS2
LHC Injectors Upgrade (LIU) completed
Phase-1 upgrades: major for LHCb and ALICE

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

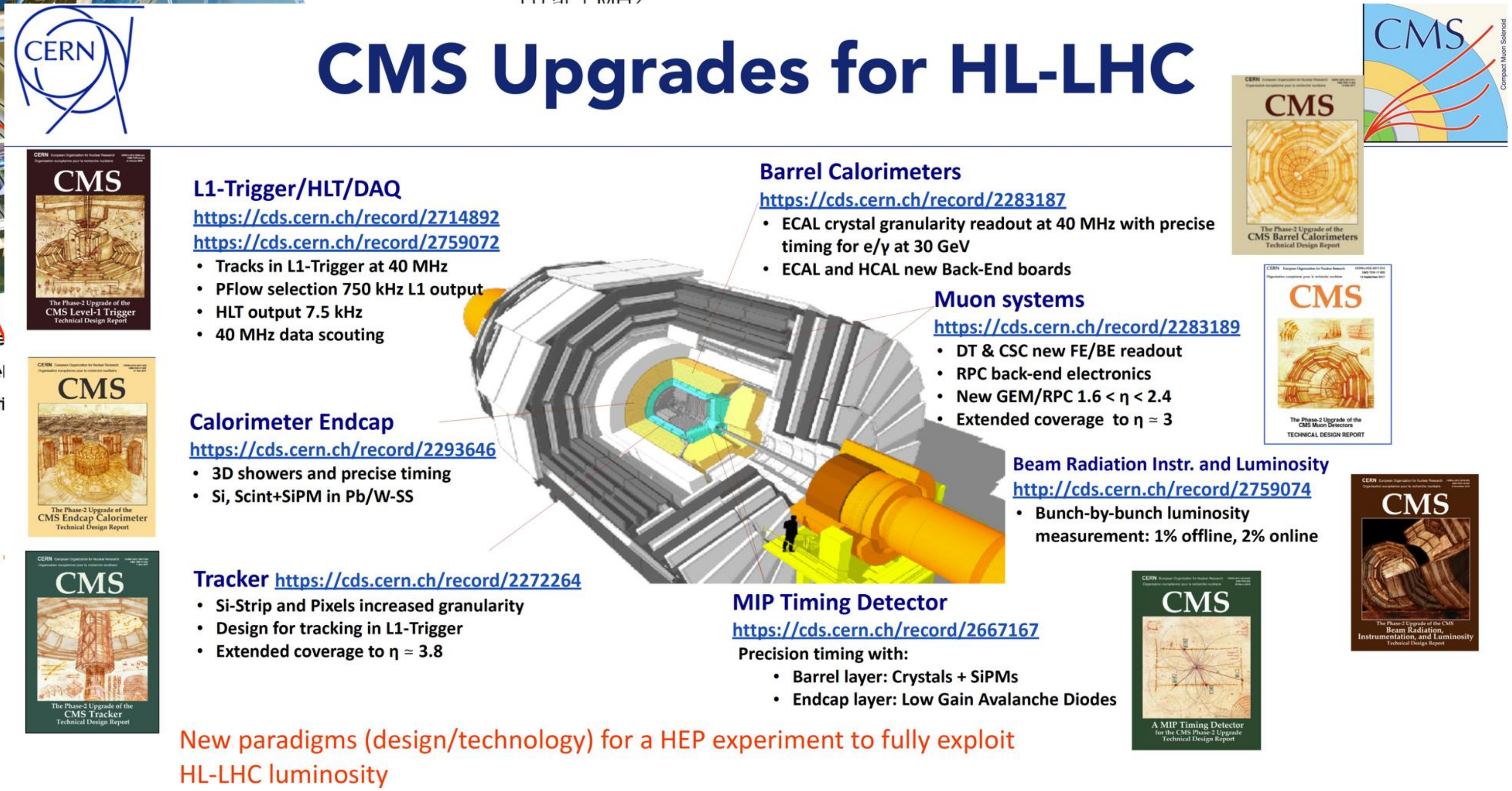






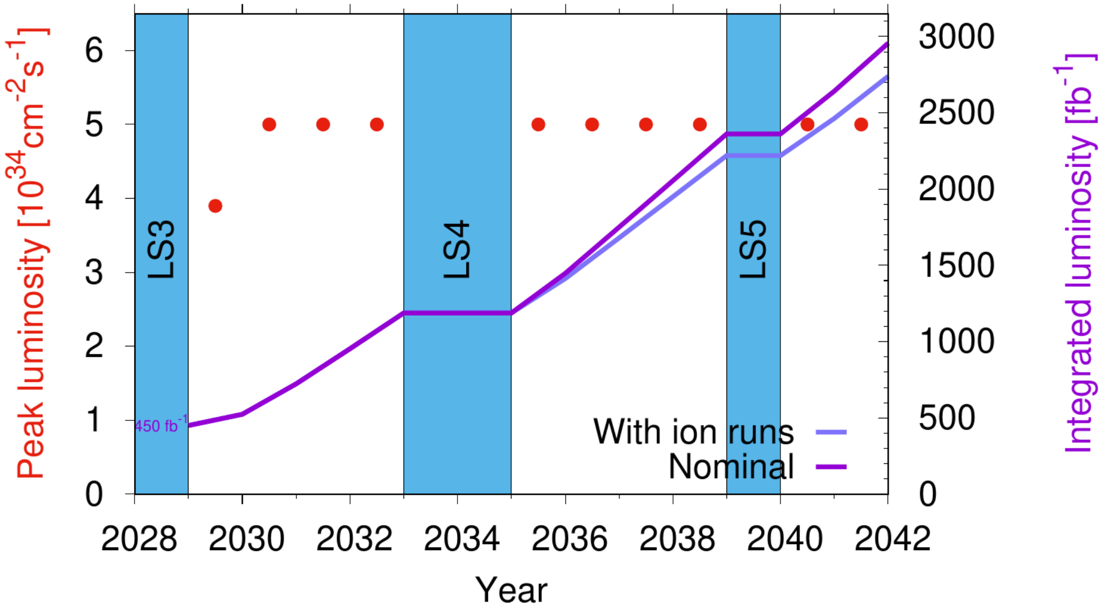
*The **HL-LHC project** is now in an advanced stage with 3/4 of the budget committed. Although schedule risks remain in several areas, the CMAC is convinced that the project will be ready for implementation in LS3.*

HL-LHC - Phase II upgrades for ATLAS and CMS



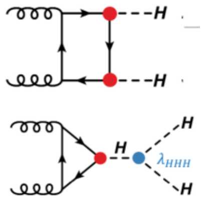
HL-LHC - full physics programme

Headline deliverable is 3 ab^{-1} proton-proton



First observation of HH production (~ 5σ level)

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



The HL-LHC offers a unique opportunity to test BSM physics

	Opportunities	**Open problem in particle physics**
Higgs & electroweak symmetry breaking	Precision program, rare events, CPV	EWSB
New particles	New resonances, squeezed spectra, long lived particles	hierarchy problem
Heavy New Physics	Effective field theories & effects in distributions at high energy	
Dark Matter/dark sector	Light dark resonances at the LHC/LHCb!	Dark matter, baryon anti-baryon asymmetry, strong CP problem,
Flavor sector	Indirect tests of flavorful New Physics	flavor puzzle

A diverse physics programme

ALICE 3 proposed for LS4

LHCb Upgrade II proposed for LS4

Forward physics

- Precision Proton Spectrometer II (PPS II)

Neutrinos

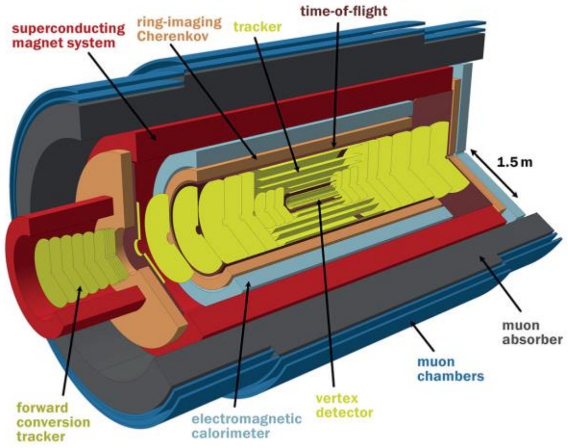
- SND, FASERnu, Forward Physics Facility (FPF)

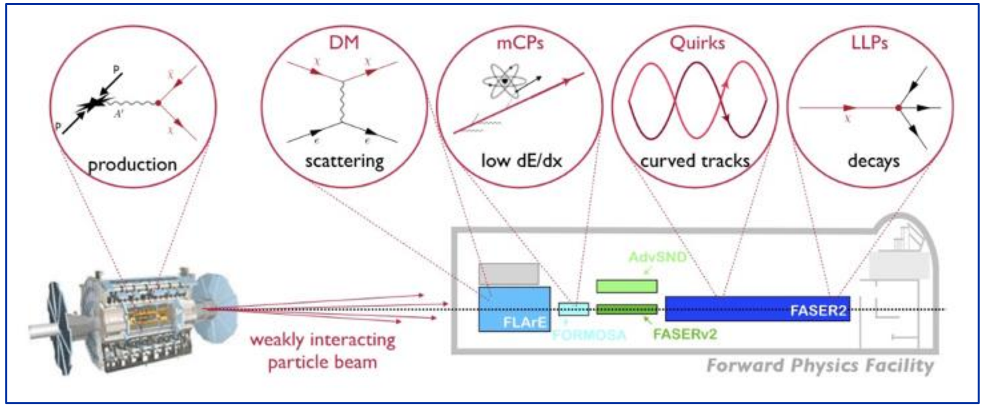
Long Lived Particles/FIPS

- GPDs, FASER, SND, MoEDAL, milliQan, FPF, CODEX-b, MATHUSLA, ANIBUS

Fixed target

- SMOG-2@LHCb, LHCspin, TWOCRYST (Λ_c^+ MDM/EDM)





Future Options at CERN

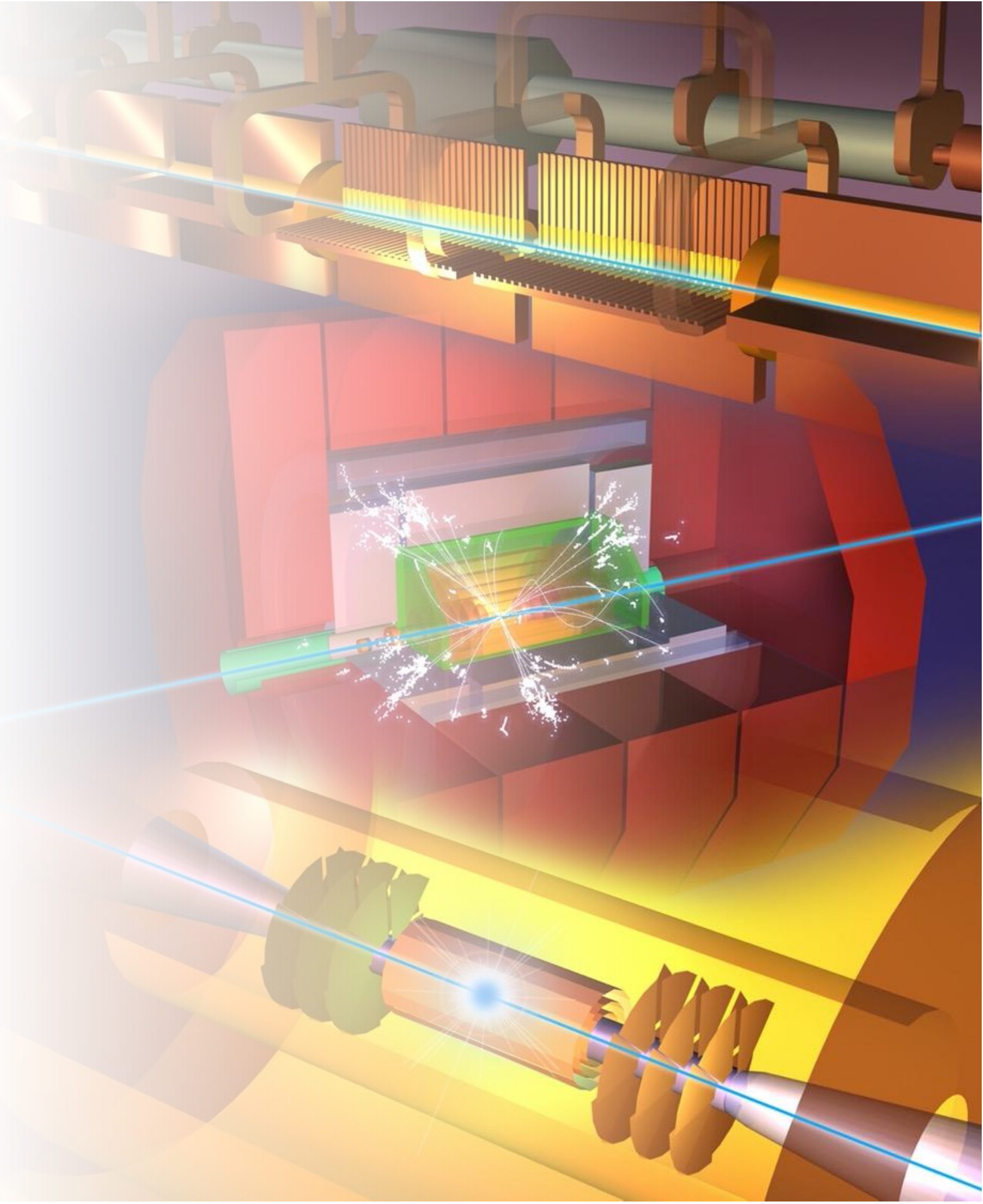
Within specified timeframe (start ops. ~2045)

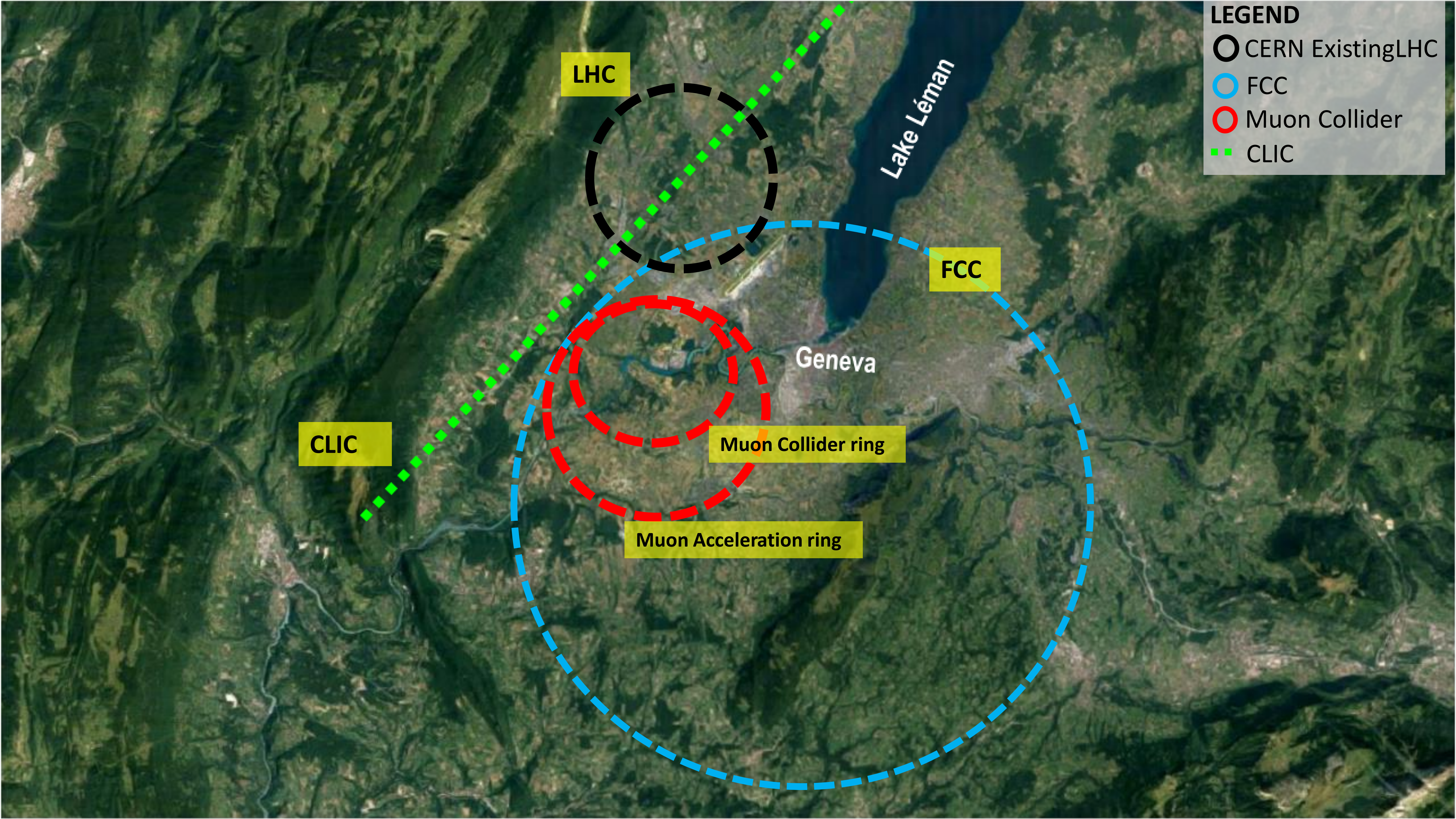
- FCC-ee
- CLIC

Outside specified timeframe

- FCC-hh - natural continuation of FCC programme
- Muon Collider

Options possibly in timeframe not at CERN: ILC, CEPC





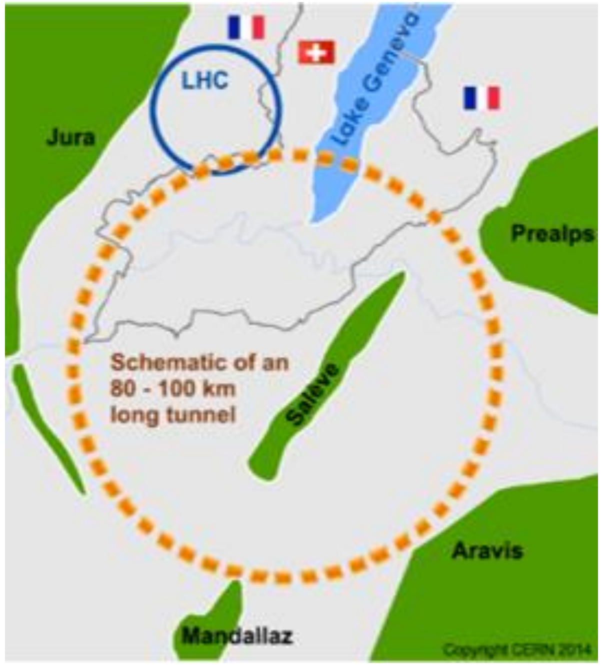
LEGEND
CERN ExistingLHC
FCC
Muon Collider
CLIC
LHC
Lake Léman
FCC
Geneva
CLIC
Muon Collider ring
Muon Acceleration ring

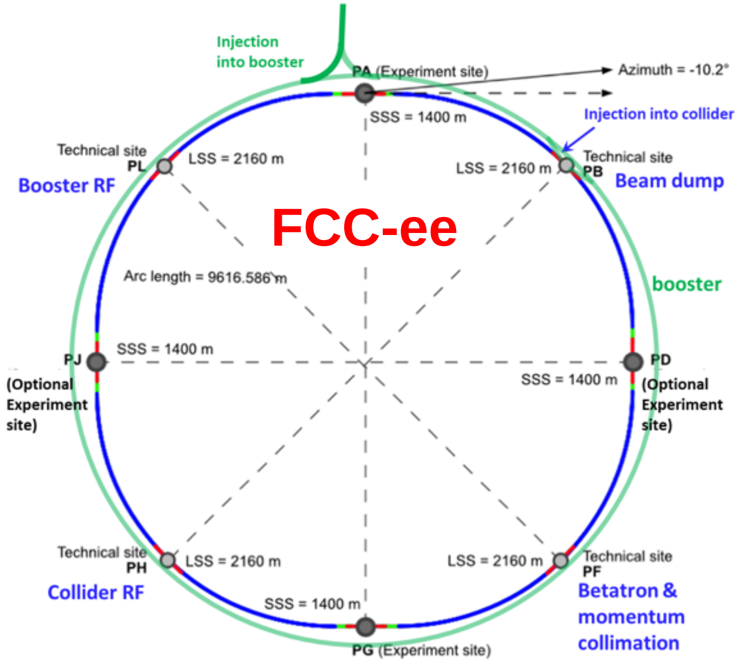

Switzerland
LHC
France
FCC
91 km circumference
LHC
PS
SPS
FCC

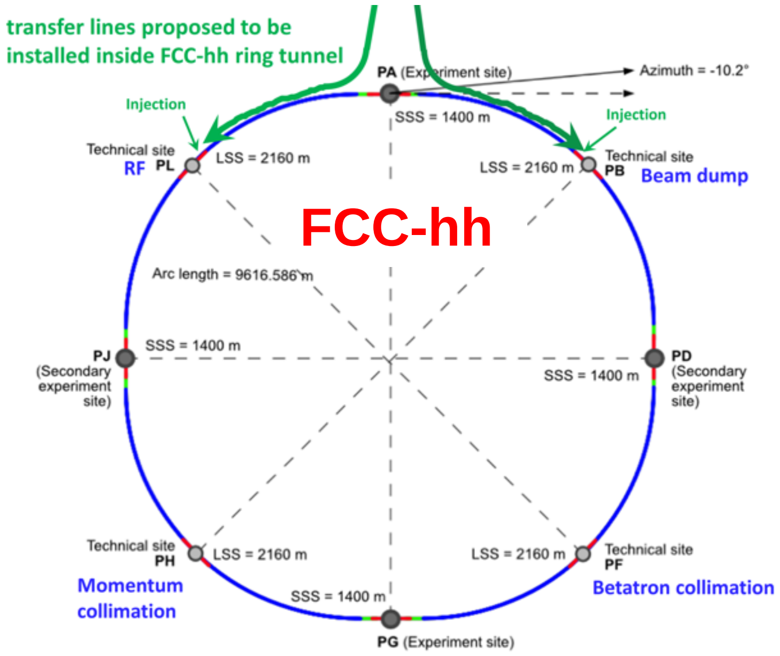
FCC Integrated Programme

Comprehensive long-term programme maximizing physics opportunities:

- Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as a Higgs factory, electroweak & top factory at highest luminosities
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, proton-proton with options







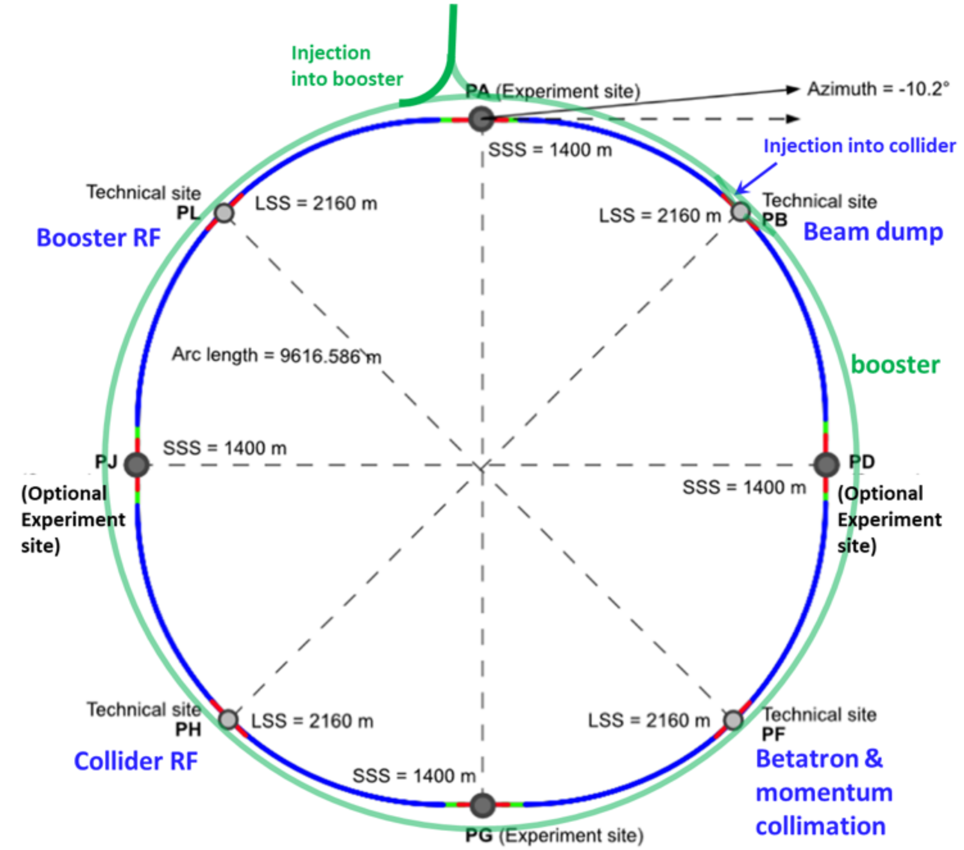
2020 - 2046 | 2048 - 2063 | 2074 +

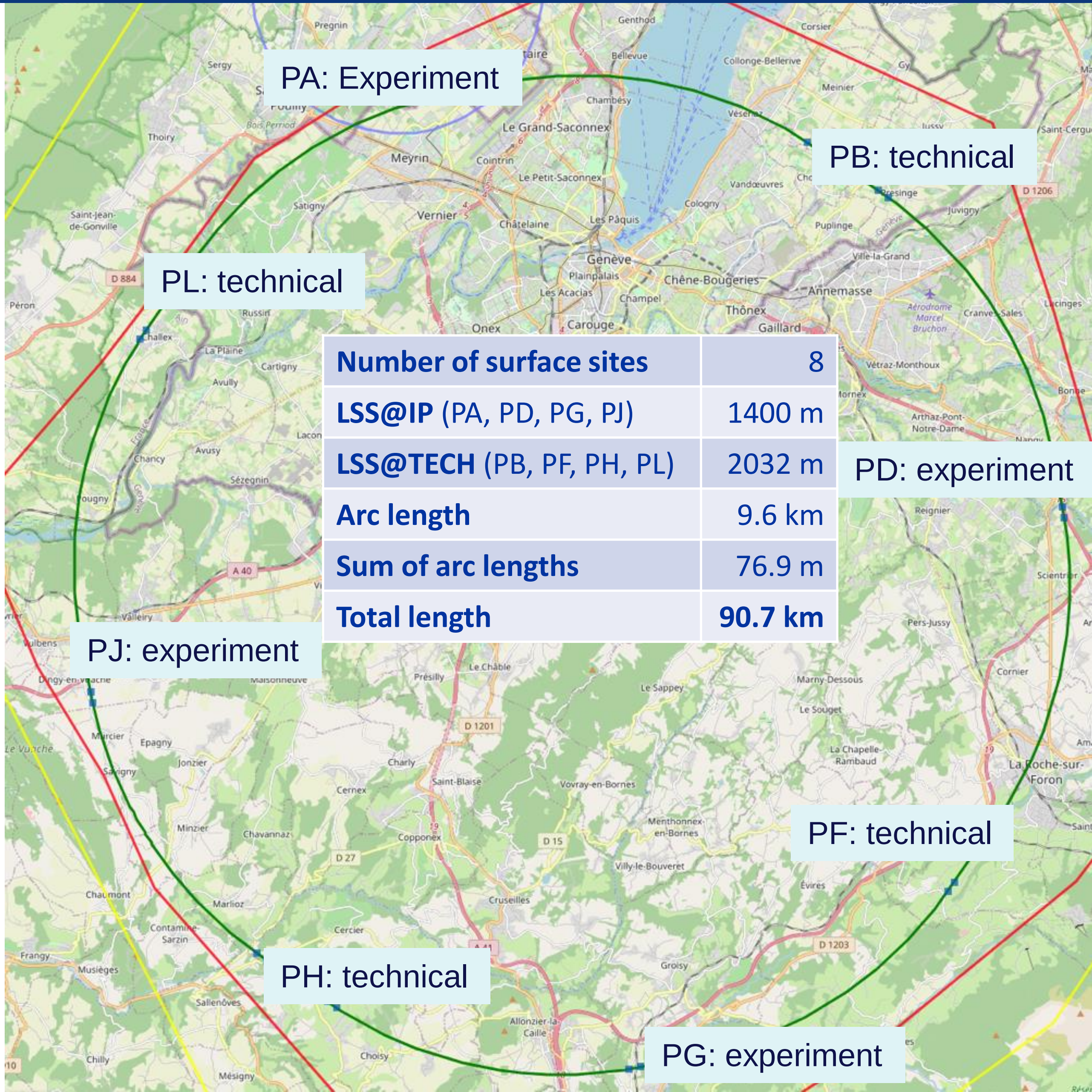
Feasibility study (2021 – 2025) ongoing

Major achievement: optimization of the ring placement
Layout chosen out of ~100 initial variants, based on geological, urban, environmental & infrastructure constraints.

Baseline: 90.7 km ring, 8 surface points

Whole study now adapted to this placement





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 m
Total length	**90.7 km**

Underground Civil Engineering Schematic

Tunnel Circumference: 90.7 km

Excavated vol: 6.2 Mm^3 (in the ground)

Access shafts: 12

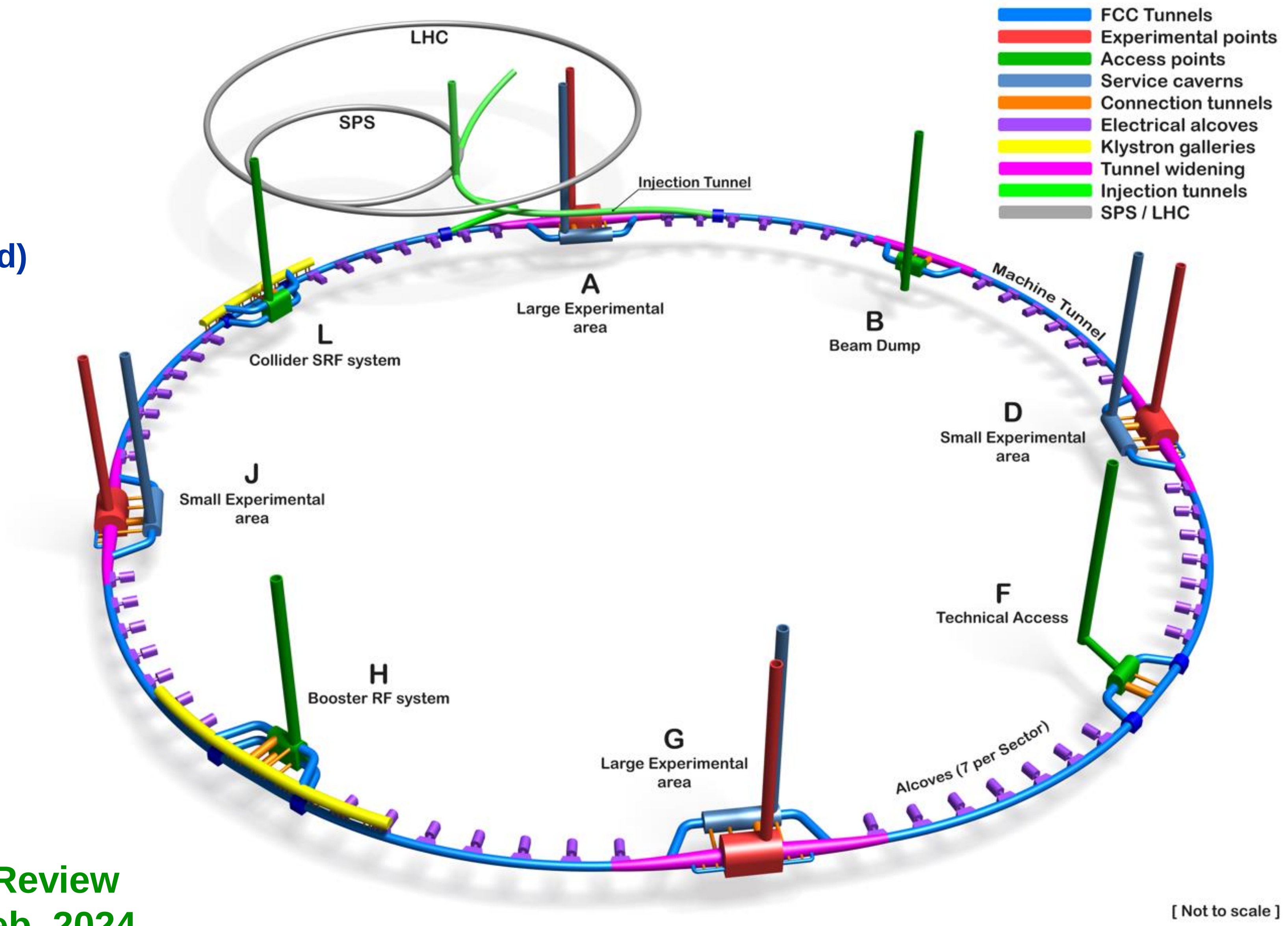
Large experiment areas: 2

Small experiment areas: 2

Technical points: 4

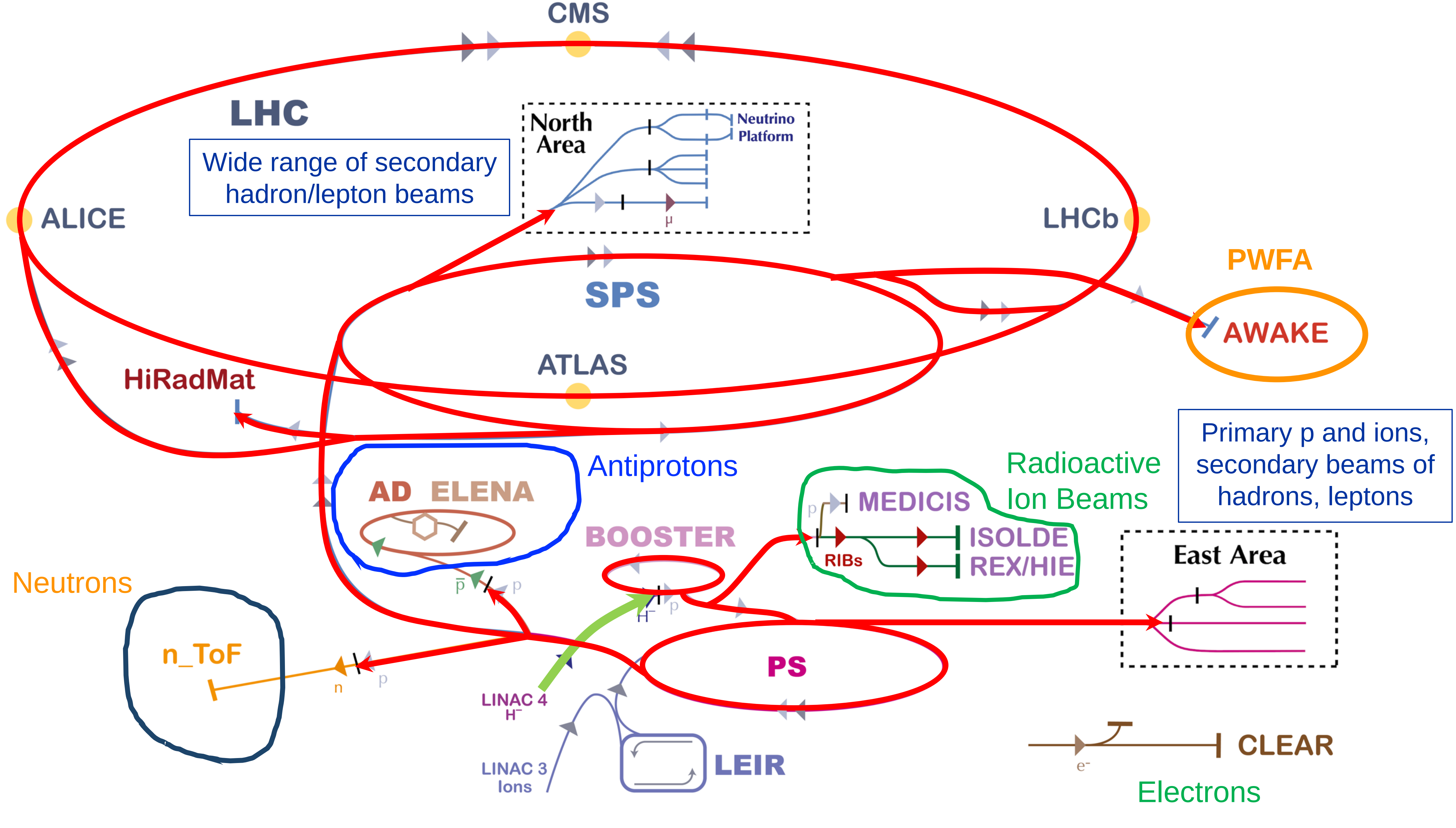
Deepest shaft: 400 m

Average shaft depth: 243 m



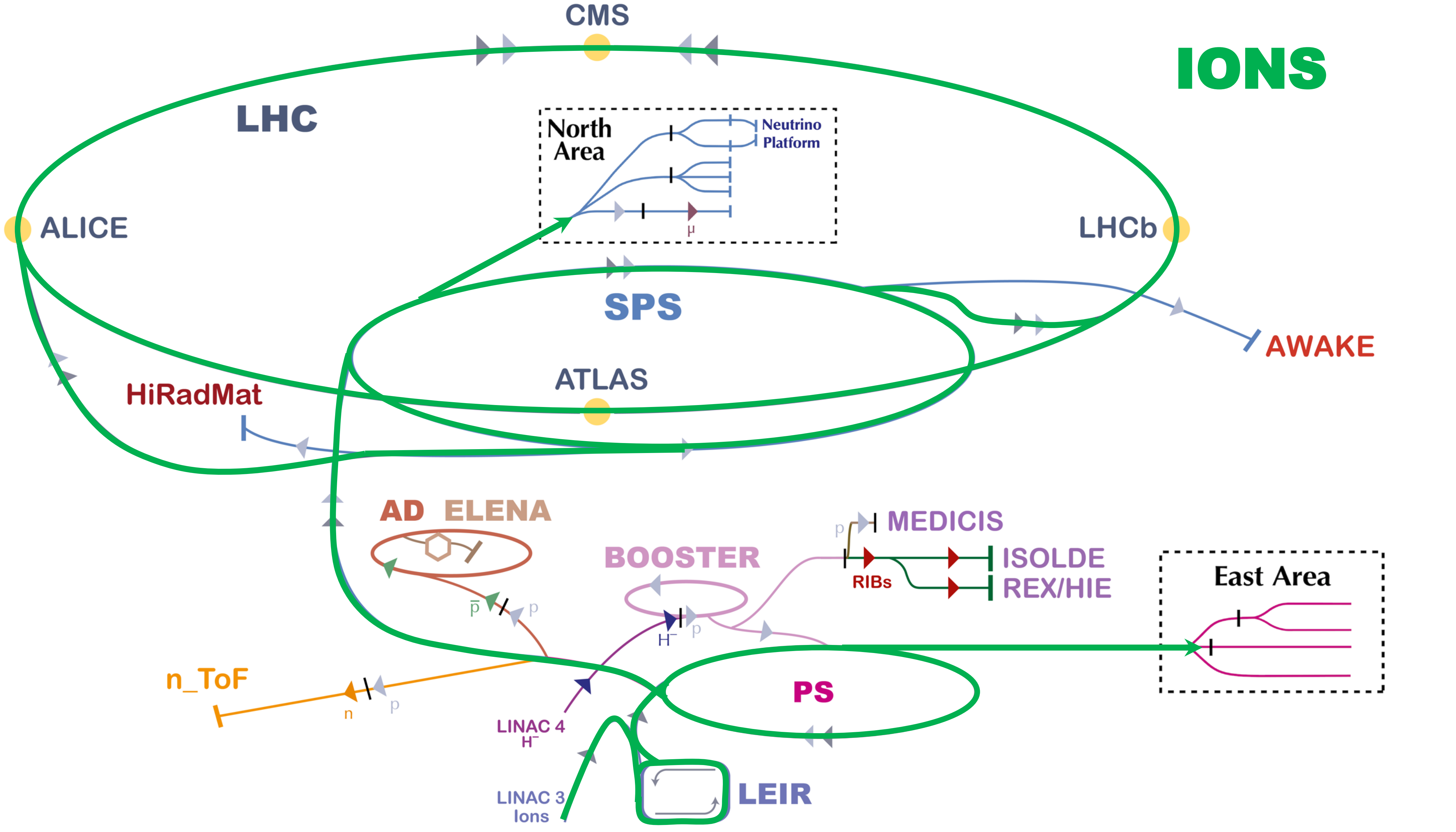
FCC Feasibility Study Mid-Term Review well received by CERN Council Feb. 2024

Indicative timelines



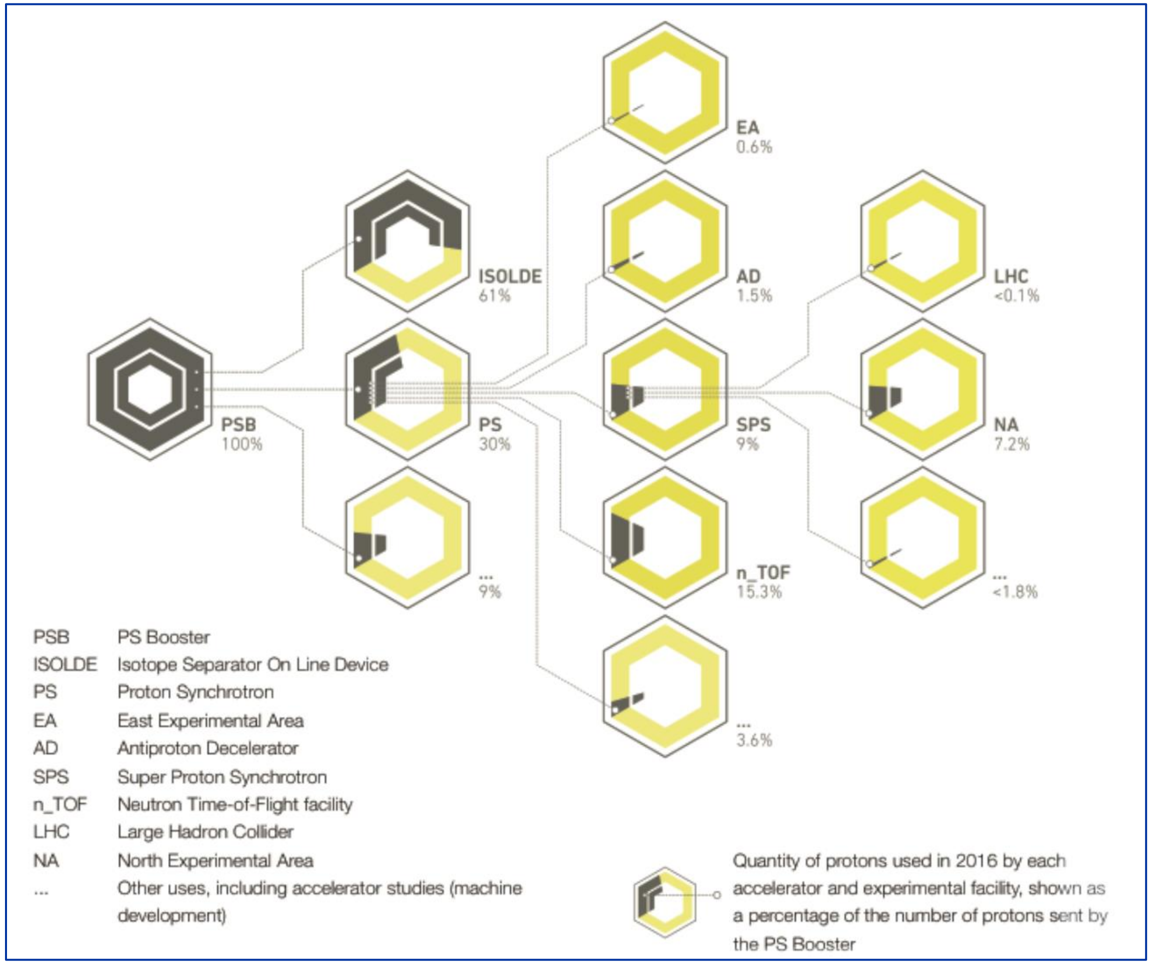
H⁻ (hydrogen anion) p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) p̄ (antiprotons) e⁻ (electrons)

IONS



H⁻ (hydrogen anion) p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) p̄ (antiprotons) e⁻ (electrons)

Protons from Booster: <0.1% to LHC



- **ISOLDE**
- **n_TOF**
- **SPS-NA**: AMBER, NA61, NA62, NA64, NA65
- **PS-EA**: CLOUD
- **AD/ELENA**: AEgIS, ALPHA, ALPHA-g, ASACUSA, BASE, GBAR
- **Neutrino Platform**: ProtoDUNE, ENUBET, ND280
- **AWAKE – proton driven wakefield acceleration**
- **HiRadMat, IRRAD, GIF, CHARM**

- **Plus a lot of test beam!**

Scientific Cultures

Nuclear Physics

	Beams	Expts	Duration	Users	Approval	
NA60+ / SHINE	Stable heavy ions, protons, hadrons	2	years	50 / 150	SPSC/RB	*focussed HI experiments*
ANTIMATTER FACTORY / ELENA	Antiprotons	6 currently	years	350	SPSC/RB	*anti-proton facility with focussed experiments.*
nTOF	Neutrons	10-15 per year	weeks	150	INTC/RB (protons)	*neutron facility with several instruments and many experiments*
ISOLDE	>1300 radioisotopes	40-50 per year	week	1000	INTC/RB (shifts) significant backlog	*radioactive beam facility with many instruments, many experiments and many beams*

(some numbers indicative)

North Area: the future is colourful and dark and interesting!

Physics motivation remains strong

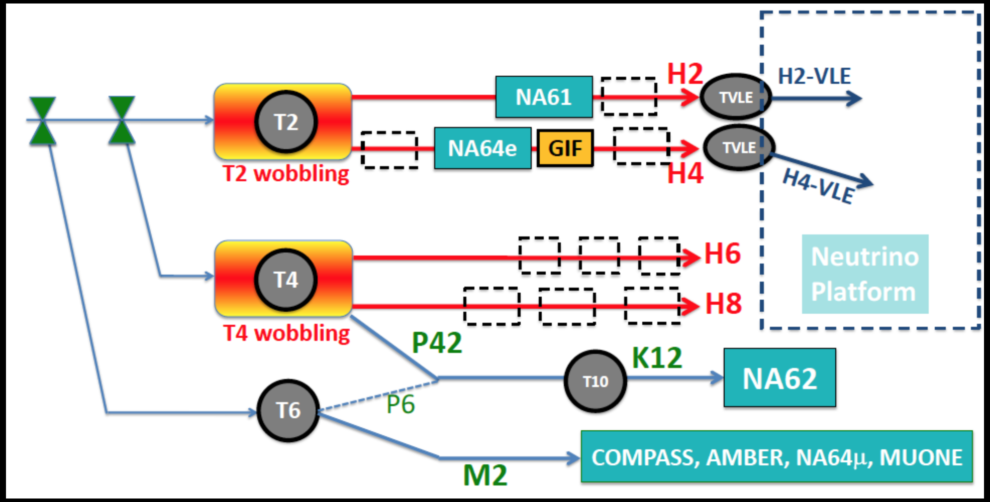
- The North Area is an ideal place to search for Hidden Sector at with NA64, SHiP etc. in < O(10) GeV range
- Unique QCD possibilities

SPS is adapting well to the foreseen challenges

NA remains vitally important as a test facility

Programme foreseen out into the 2040s

Backed by a major 2 phase consolidation project

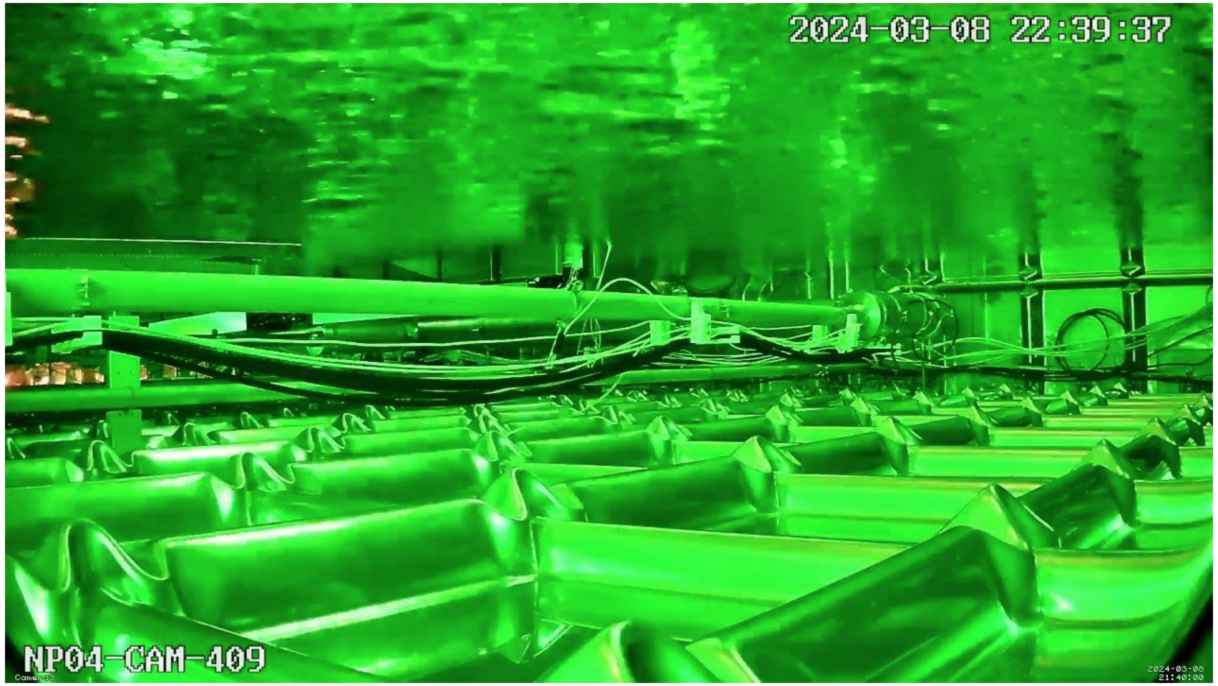


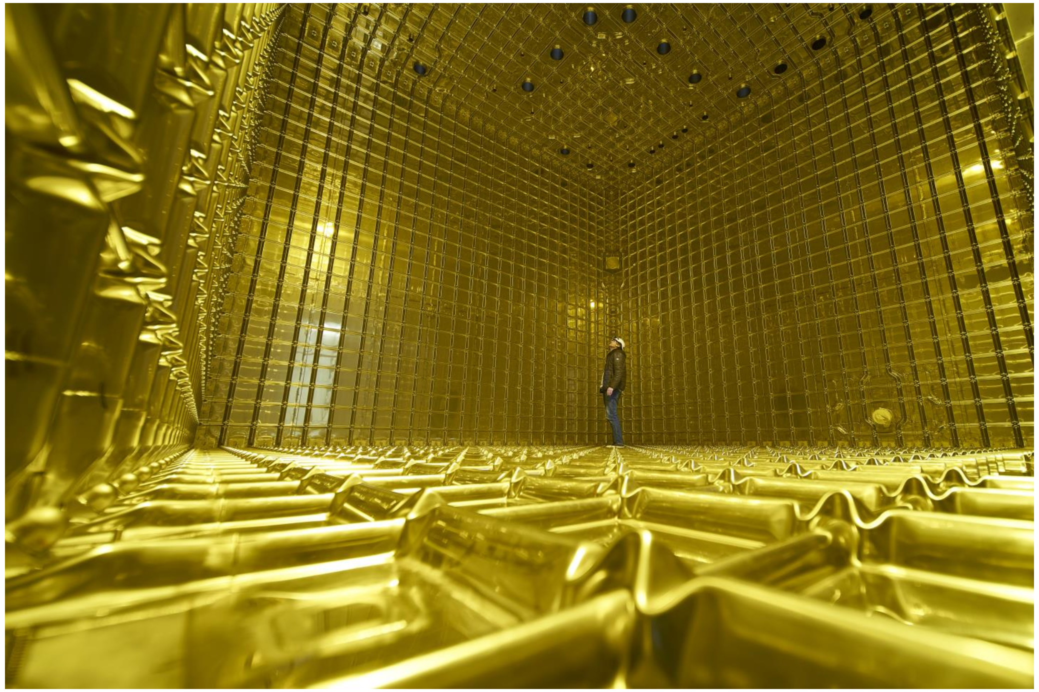
Neutrino Platform at the North Area

Recently - installation in the cryostats of the two final prototypes for the far detector of the DUNE experiment was completed

Tests with beams will start after filling with liquid argon…

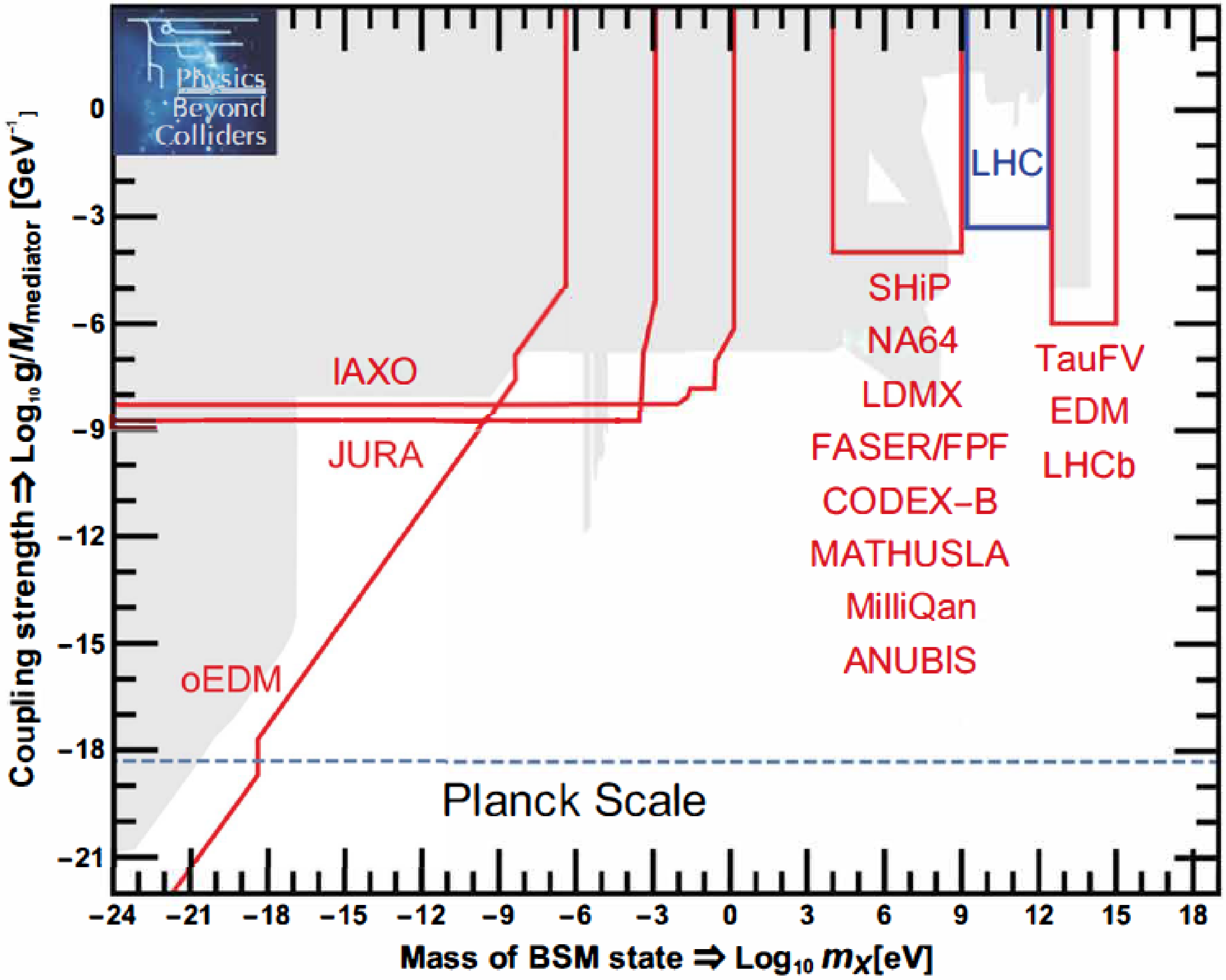
Filling NP04 (H drift) with Liquid Argon





Physics Beyond Colliders

complementary methods to high-energy-frontier colliders



Location	Experiment	Physics case
NA/H4	NA64-electron	Dark photon - electron active beam dump
NA/M2	NA64-muon	Dark photon - muon active beam dump
NA/H2	NA61++	Charm in QCD Phase transition
NA/EHN1	NA60++	High-μB region of the QCD phase diagram
NA/M2	MUonE	Hadronic Vacuum Polarisation contribution to (g-2)μ
NA/M2	COMPASS/AMBER	QCD dynamics - generic program
SPS/BDF	SHiP	Dark sector, tau neutrinos
LHC	FASER	Long lived particles
LHC	SND	Neutrinos
LHC	FPF	FASER2, FASERnu, advSND, FORMOSA, FLARE
LHC	MATHUSLA	Long lived particles
LHC	CODEX-b	Long lived particles
LHC	milliQan	Long lived particles/fractional charge
LHC	ANIBUS	Long lived particles
LHC	LHC Spin	QCD dynamics and phase transition
LHC	2-crystal	MDM/EDM of short lived baryons
SPS	AWAKE++	Dark photon
CERN	VMB	Vacuum Magentic Birefringence
CERN	JURA	Axion/ALPS search (LSW)
DESY	BabyIAXO/IAXO	Axion search - helioscope
DESY	ALPS	LSW
CERN	AION-100	GW, ultra-light dark matter
SPS	ENUBET/NuTag	Novel nu beams
Jülich	pEDM	Polarized protons for EDM storage ring measurement
SPS/LHC	Gamma Factory	High intensity gamma ray beam

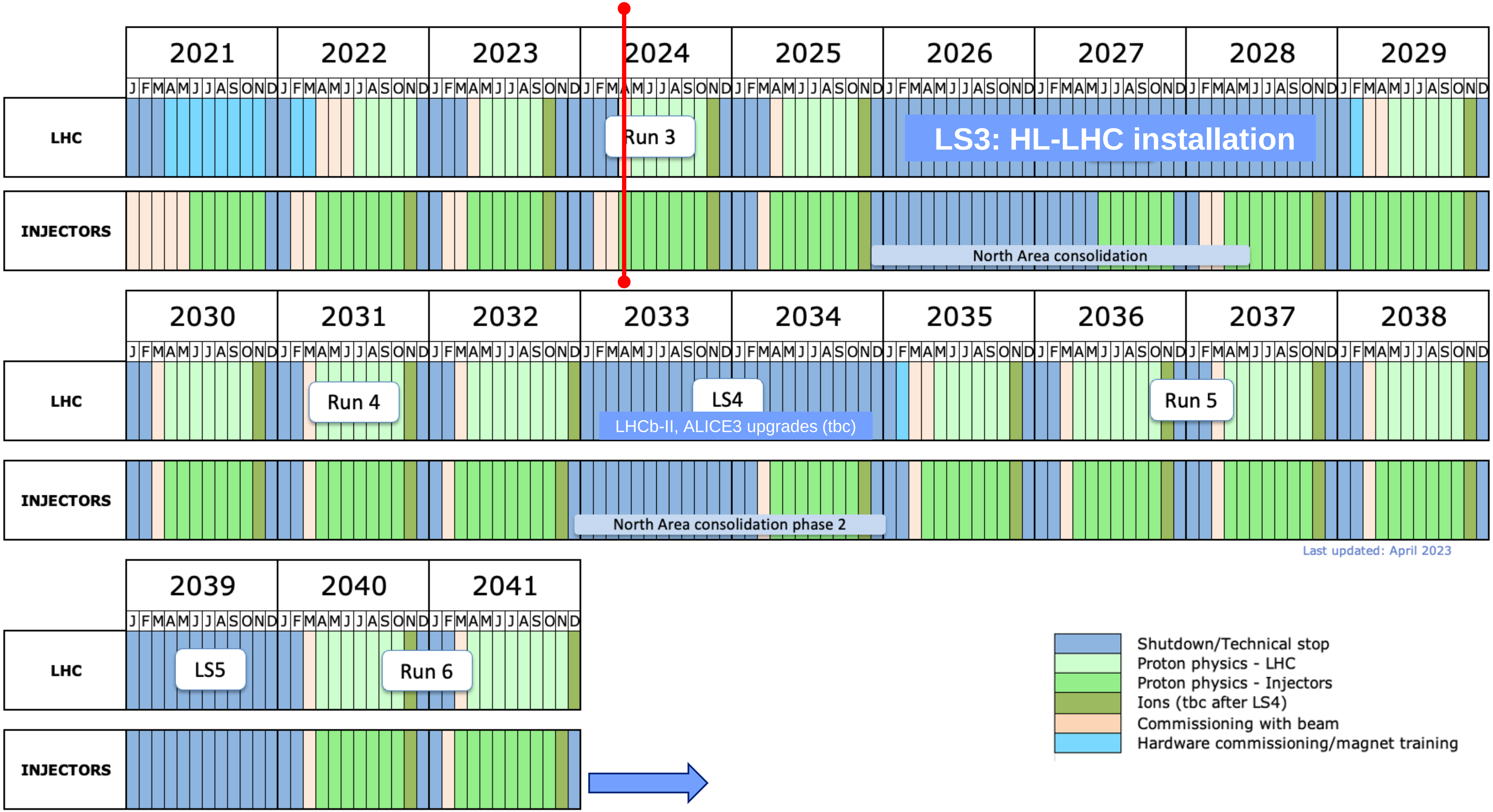
Complex timeline

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
L4, PSB, PS						LS3							LS4						LS5		
L3, LEIR						LS3							LS4						LS5		
SPS						LS3							LS4						LS5		
LHC		Run 3				LS3			Run 4				LS4						LS5		
CLEAR	Review			Review																	
ISOLDE						BD							LS4						LS5		
HIE-ISOLDE													LS4						LS5		
MEDICIS			Review																		
n_TOF													LS4						LS5		
EAST AREA													LS4						LS5		
ELENA													LS4						LS5		
AWAKE	AWAKE Run 2a,b				CNGS			Run 2c		Run 2d											
North Area						NA-CONS Ph1							NA-CONS Ph2						LS5		
ECN3/SHiP				Construction															LS5		

Approved   tbc

Good for the next 10 years, clear potential beyond that…

HL-LHC era - indicative timeline



Technology

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Accelerator R&D Roadmap

European Strategy Update

LDG Laboratory Directors Group

Accelerator Technologies and R&D
RF technologies R&D (SRF, X-band)
High-field superconducting accelerator magnets R&D
Proton-driven plasma wakefield acceleration (AWAKE)
CERN Linear Electron Accelerator for Research (CLEAR)
Other targeted accelerator R&D (Vacuum, Materials…)

Targets
Beam Incepting Devices
Beam dumps
Collimators
Beam instrumentation
Radiofrequency
Low temperature superconductors
High temperature superconductors
Cryostats
Superconducting magnets
Resistive magnets
Vacuum
Coatings
Cryogenics
Power converters
Rad-hard electronics
Precison timing
Robotics
Pulsed Power Engineering
Kickers
Septa
Fast electronics
Controls

Detector R&D

See Chris Parkes later this morning

Status DRD Collaborations

- DRD1 Gaseous detectors
- DRD2 Liquid Detectors
- DRD4 Photodetectors & PID
- DRD6 Calorimetry

Fully approved by RB Dec 2023 on recommendation of the DRDC

- DRD3 Semiconductor Detectors

Conditionally approved

- DRD5 Quantum Sensors
- DRD7 Electronics

DRDC received full proposal in March 2024

- DRD8 Integration

Full proposal expected end 2024

CERN as a Research Infrastructure

CERN evolved before the RI concept

But nonetheless, thanks to its governance and funding model, many of the ingredients are there

Fortunate to enjoy a clear mission, strong support from our member states and international partners, and a culture of transparency and openness

The RI paradigm is important and it is how we are viewed by, say, the European Commission

- Drive discovery and creation of knowledge
- Driver of innovation
- Integration of research communities
- Strong links to industry
- Collaborative ecosystem
- Societal impact
- Outreach and education

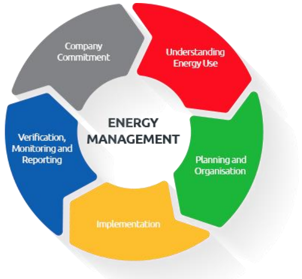
Sustainability - energy

LOW-CARBON ELECTRICITY

Pulling from French grid – low carbon (nuclear & renewables)

ISO 50001 CERTIFICATION

Energy Management - Improvement goals, continuous monitoring – EM plan & panels



POWER PURCHASE AGREEMENTS

Two photovoltaic PPA agreements being pursued for ~135 GWh/year ~10% of our supply

RESOURCE MANAGEMENT

PPAs (Nuclear, PV, aggregation) EU market reform, new contracts, water, gas, helium…

Summary - targeting CERN's strategic goals

HL-LHC - flagship out to end 2041

Complementary scientific diversity programme - full, safe, exploitation of the remarkable potential of the complex – longevity & possible facility upgrades. Backed by a strong technology and engineering base and support facilities.

In the longer term, the preferred direction for a future collider at CERN is the FCC: feasibility study to be delivered in 2025. Alternatives pursued as plan B (CLIC, Muon Collider) plus agreed support to ILC

Execution of European R&D Roadmaps plus Quantum, AI etc.

CERN as a Research Infrastructure. European integration via diverse Horizon projects. Leverage position as nexus of an impressive collaborative ecosystem.

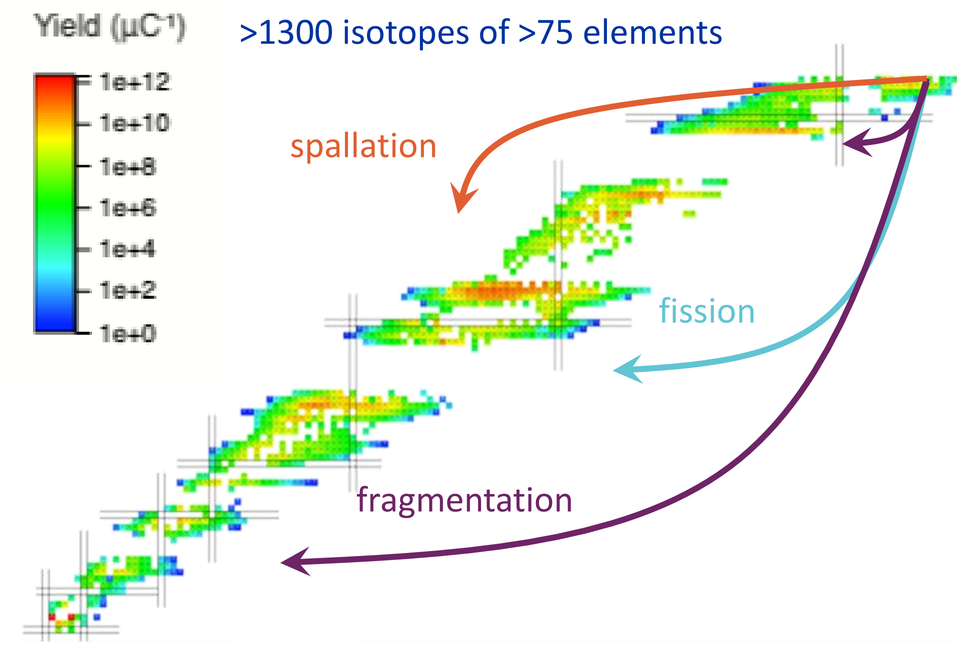
Sustainability and Societal impact, Outreach and Education as key parts of our mission

Backup

The *only* radioactive ion beam facility using GeV protons - several processes (fission, spallation, fragmentation) all contribute to radioisotope production on a particular target gives wide range of isotopes with excellent yields.

Easy and quick delivery of different isotopes for *precision studies across many isotopes* with systematics under control.

>15 *state-of-art instruments*, cutting-edge in laser spectroscopy, mass traps, detector arrays, particle spectrometers…



Very close collaboration between ATS groups and users is an important *strength* at CERN.

ISOLDE Improvement Programme

Up and including LS3:. Several "consolidation plus improvement" items to ISOLDE infrastructure to assist both capacity and capability – important opportunity to increase isotope yields via proton energy & intensity.

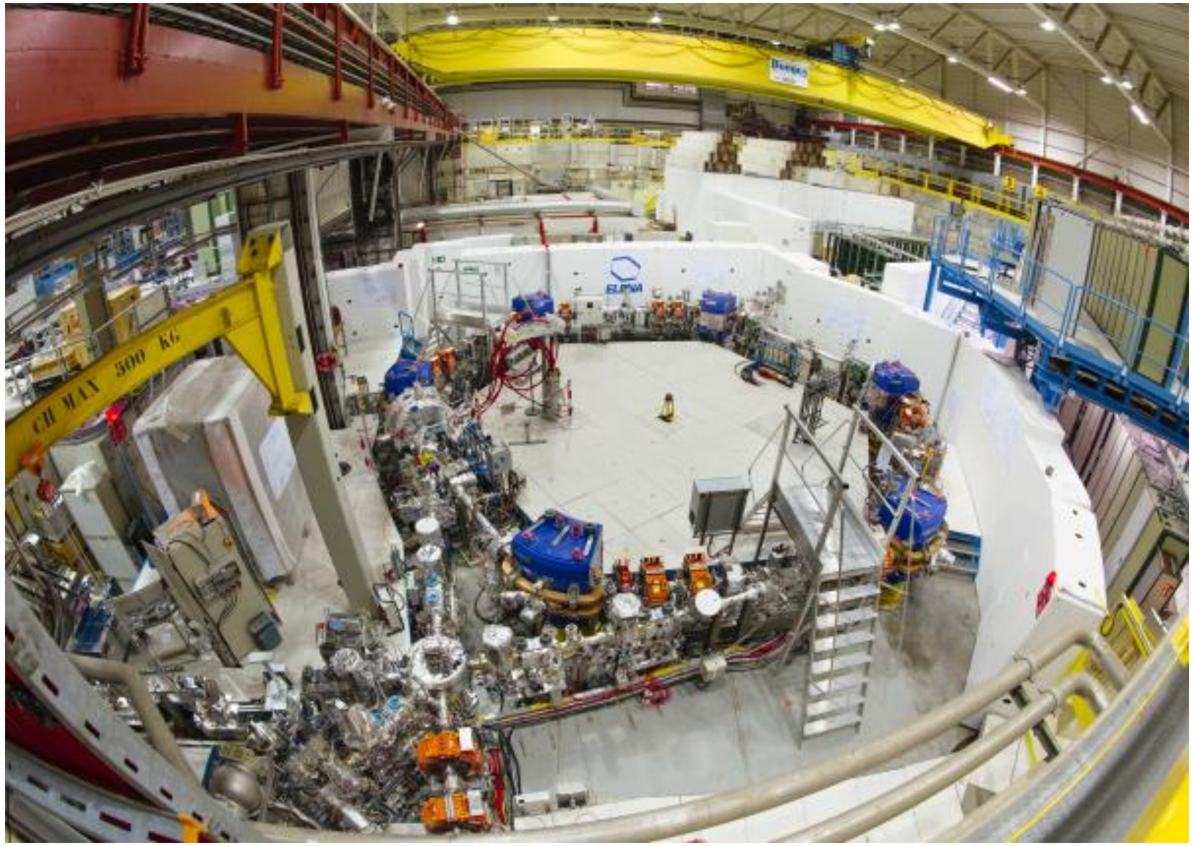
Longer term LS4+: upgrades for enhanced EBIS/Trap feeding HIE-ISOLDE; linac upgrades to higher energies; hall extension… *for further discussion in coming years.*

ANTIMATTER FACTORY

ELENA

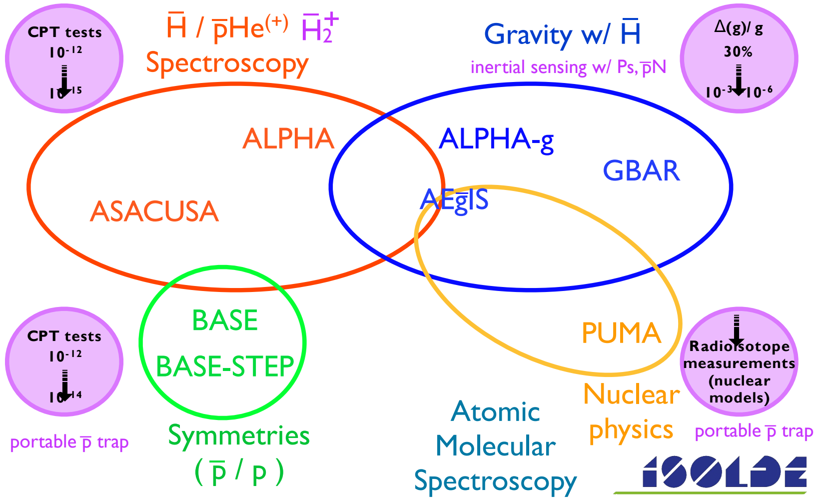
AD has potential to change physics at a fundamental level and CERN is the only place in the foreseeable future!

- Anti-proton Decelerator (AD) and Extra Low ENergy Antiproton (ELENA) ring
- ELENA: 100 keV antiprotons bunched to 100 ns FWHM, increasing efficiency for subsequent trapping by factor of 10-100.
- AD running since early 2000s and physics with ELENA since 2021 (Run 3)



- Advanced charged plasma control techniques
- Advanced magnetic trapping
- High power UV-laser technology
- Non-destructive quantum-transition spectroscopy
- Ultra-low-noise trapping techniques
- Sympathetic cooling and quantum-logic spectroscopy

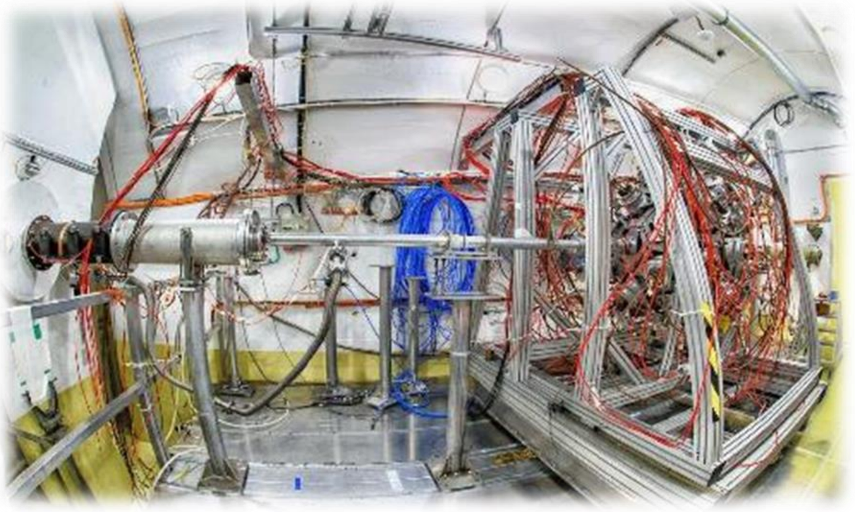
AD Future (10+ years)



n_TOF

Pulsed neutron source to study **neutron-nucleus interactions** through the **Time Of Flight (TOF)** technique

Large range of applications: astrophysics, nuclear physics, applications of nuclear technology, transmutation of nuclear waste, Accelerator-Driven-System etc.



n_TOF *unique globally* amongst TOF facilities due to favourable duty cycle, energy range and intensity:

- widest range of energies meV to GeV.
- highest instantaneous intensity.
- longest flight path with short pulses (7 ns) give excellent time/neutron energy resolution.
- low repetition rate avoids overlap of fast/slow neutrons from different pulses.
- low background environment.

Emerging science opportunities (10+ years)