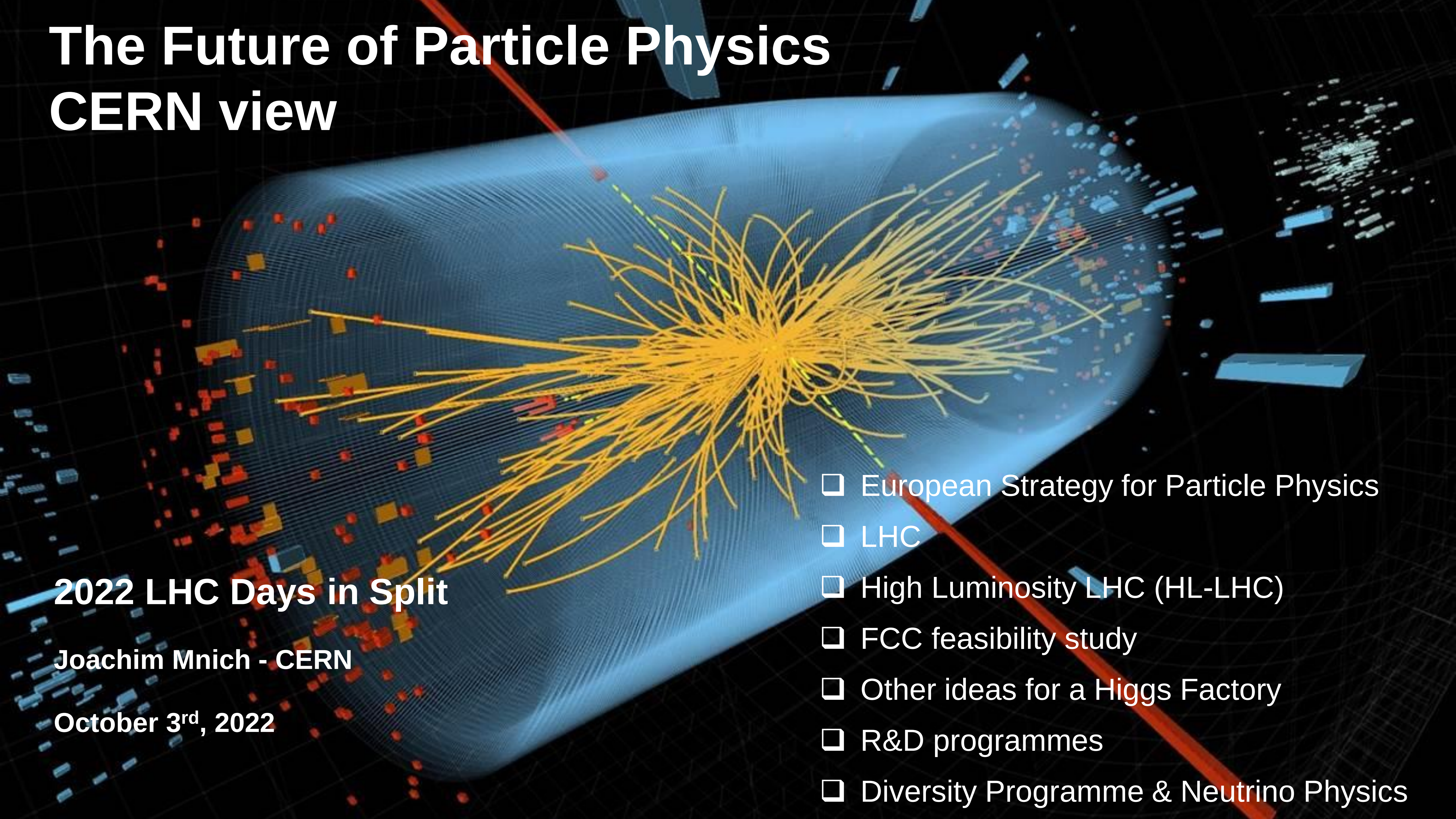


The Future of Particle Physics
CERN view

- European Strategy for Particle Physics
- LHC
- High Luminosity LHC (HL-LHC)
- FCC feasibility study
- Other ideas for a Higgs Factory
- R&D programmes
- Diversity Programme & Neutrino Physics

2022 LHC Days in Split

Joachim Mnich - CERN

October 3rd, 2022

The good news: the future has just started!

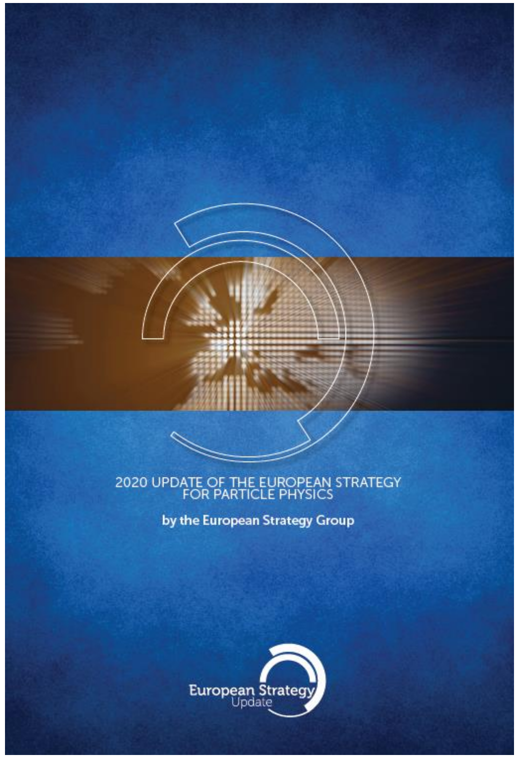
First Stable Beams at the record energy of 13.6 TeV – 5th July

Reminder Update European Strategy for Particle Physics

CERN Council updated the European Strategy for Particle Physics in June 2020

Scientific recommendations

- Full exploitation of the LHC and HL-LHC
- Highest-priority next collider: e+e- Higgs factory
- Increased R&D on accelerator technologies
- Investigation of the technical and financial feasibility of a future ≥ 100 TeV hadron collider
- Long-baseline neutrino projects in US and Japan
- High-impact scientific diversity programme complementary to high-energy colliders
- R&D on detector and computing
- Theory



Other high priority items:

- Exploit synergies with neighboring field, in particular nuclear and astroparticle physics
- Mitigate environmental impact of particle physics
- Invest in next generation of researchers
- Support knowledge and technology transfer
- Public engagement, education and communication

Importance of collaboration between CERN and national labs highlighted

This strategy provides guidelines to CERN and the entire field for the coming years

Large Hadron Collider (LHC)

Achievements since the Higgs Boson Discovery

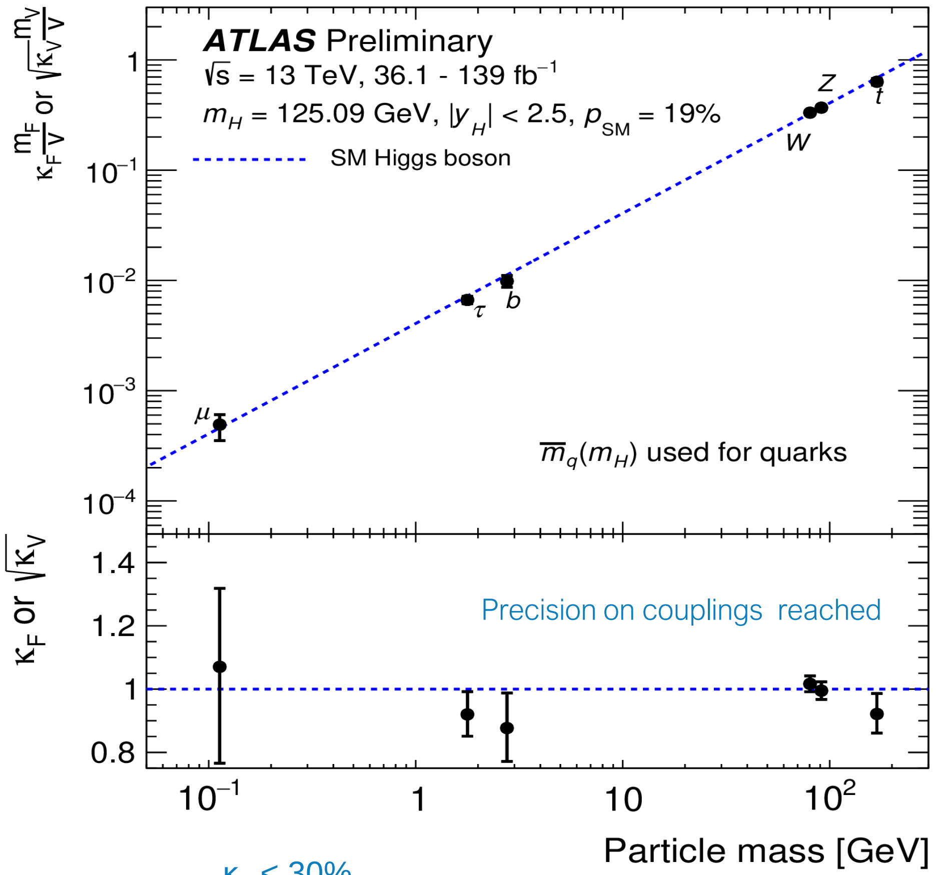
Example: measurement of the Higgs couplings to fundamental particles

ATLAS result based on the full data set (Run 2)

Impressive verification with an accuracy often better than 10%

Coupling measurements ($B_i = B_u = 0$)

$\kappa_\gamma = 1.04 \pm 0.06$, $\kappa_g = 0.92^{+0.07}_{-0.06}$, $\kappa_{Z\gamma} = 1.37^{+0.31}_{-0.37}$

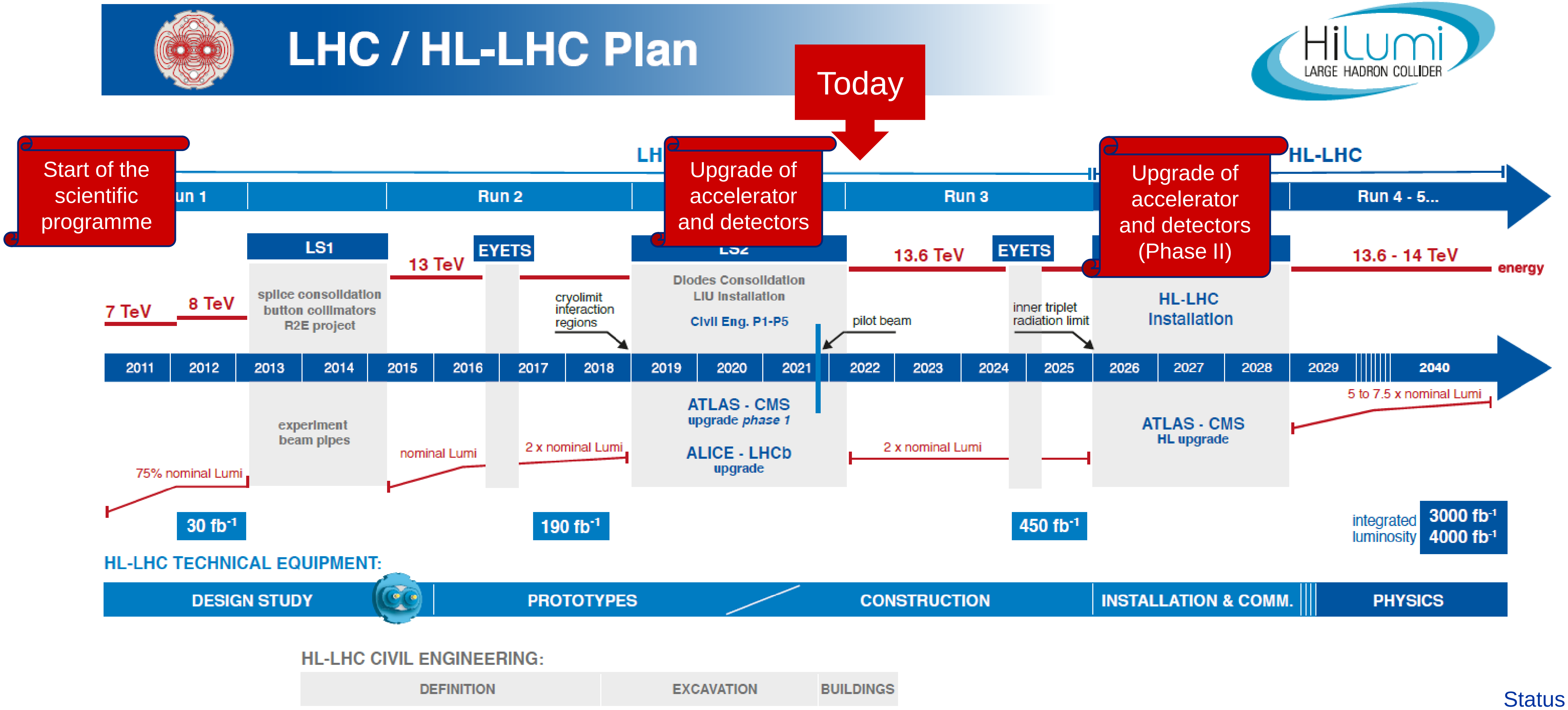


ATLAS-CONF-2021-053

$\kappa_\mu < 30\%$

$\kappa_\tau = 7\%$ $\kappa_b = 11\%$ $\kappa_t = 6\%$ $\kappa_{W,Z} = 6\%$

The LHC Scientific Programme

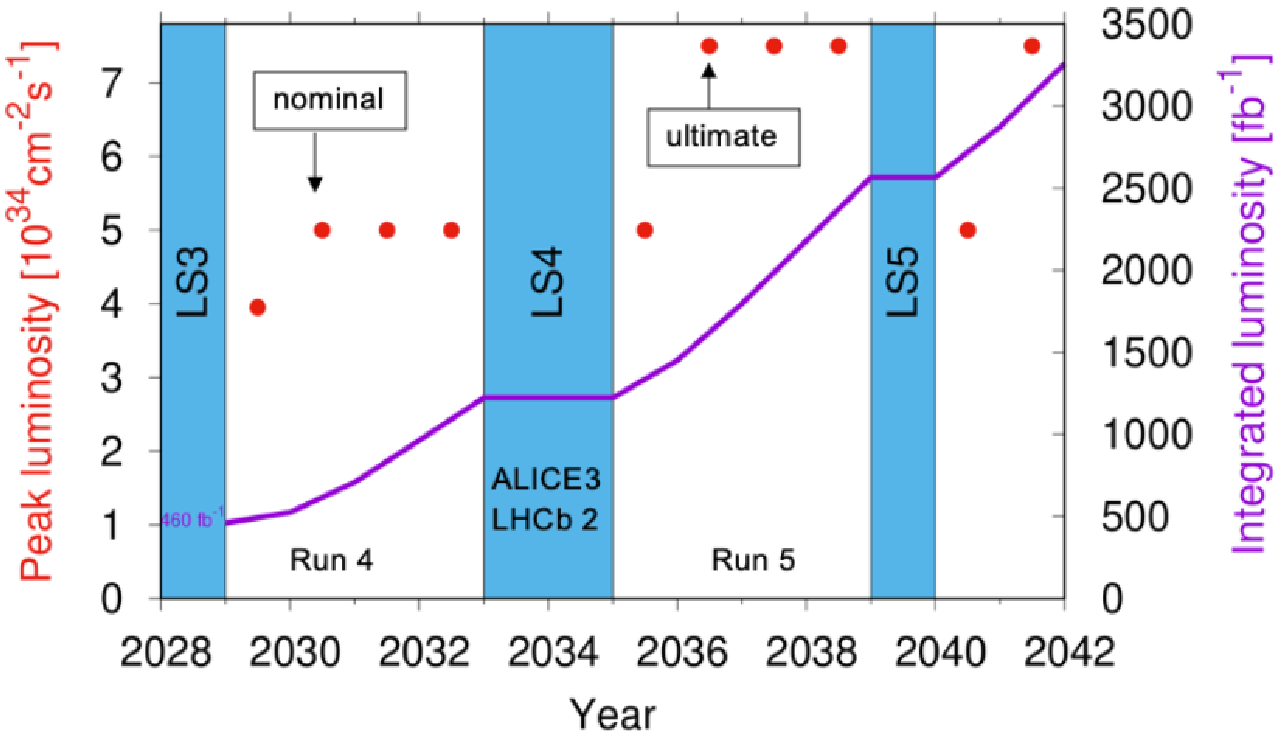


Status Feb 2022

LHC Programme

- 2022: LHC restart (Run 3)
  - Over the last years significant improvements on accelerator (incl. HL-LHC preparations) and detectors
  - Goal for Run 3 is to approx. double the luminosity for ATLAS and CMS
  - Even more potential for ALICE and LHCb due to increased rate capabilities
- HL-LHC
  - Long shutdown 2026 - 28 to upgrade accelerator and detectors (ATLAS & CMS)
  - Will increase luminosity by factors 5 to 7
- Final goal is ≥ 3000 fb^{-1}
  - About 20 times the luminosity collected until today
- ALICE and LHCb upgrades planned in the 2030ies

Preliminary HL-LHC schedule



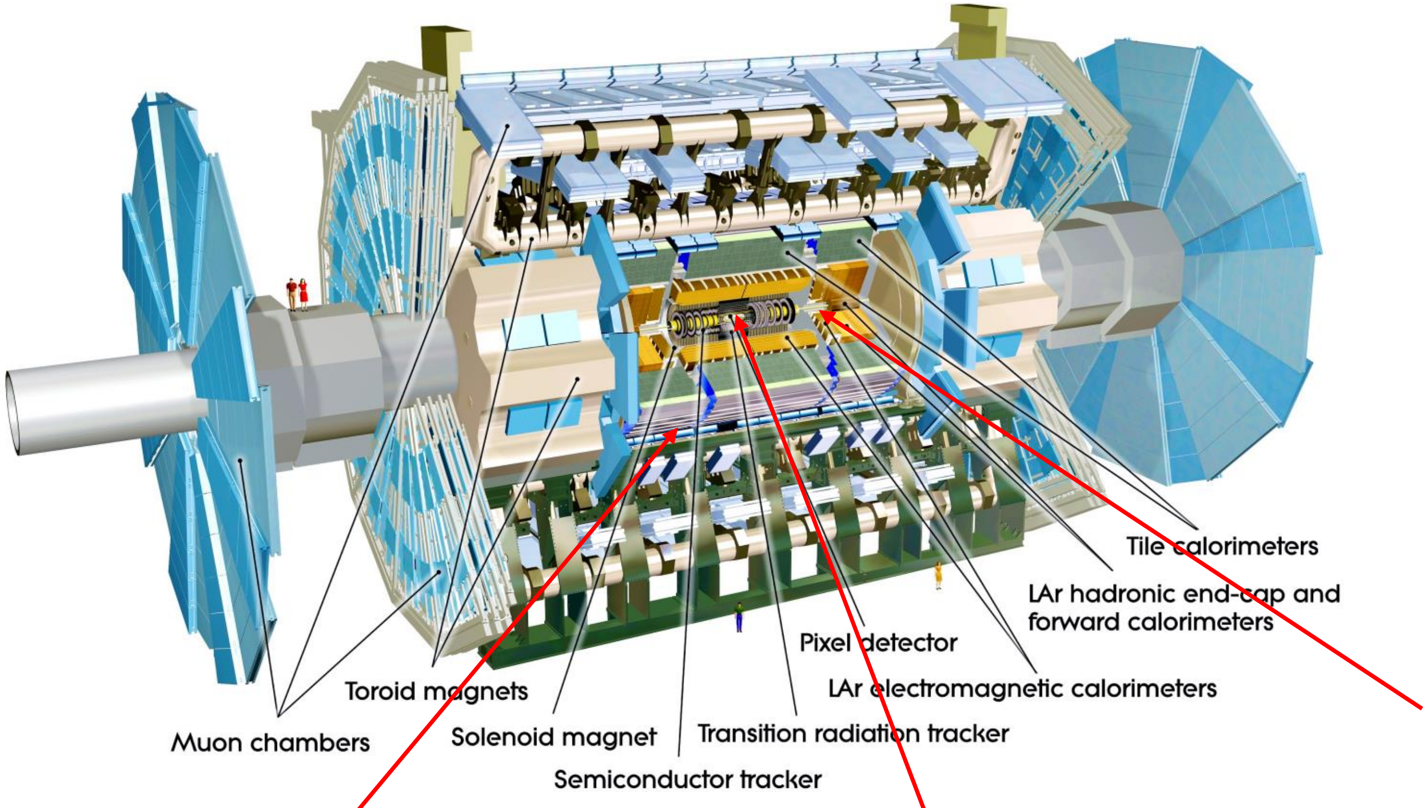
Warning: we are living in uncertain times: global economy, energy, politics,…

ATLAS Phase II Upgrades

The full scientific exploitation of the HL-LHC requires major upgrades of the detectors, mainly for ATLAS and CMS

- ❑ Higher granularity
- ❑ Better resolution in space and time

→ Phase II upgrades



Upgraded Trigger and Data Acquisition system

L0 at 1 MHz

Improved High-Level Trigger (100 kHz full-scan tracking)

Electronics Upgrades

LAr Calorimeter

Tile Calorimeter

Muon system

High Granularity Timing Detector (HGTD)

Forward region

Low-Gain Avalanche Detectors (LGAD)

New Muon Chambers

Inner barrel region

New Inner Tracking Detector (ITk)

Pixel and Strip detectors

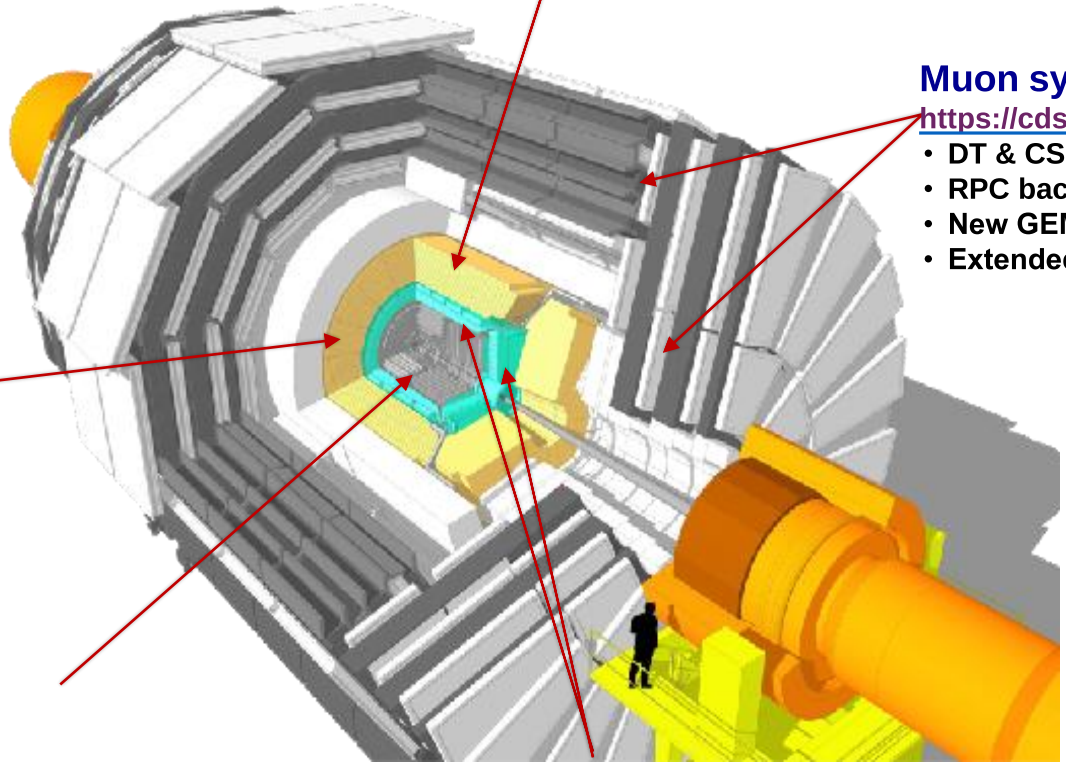
All silicon, up to |η| = 4

CMS Phase II Upgrades

L1-Trigger HLT/DAQ
https://cds.cern.ch/record/2714892
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity
http://cds.cern.ch/record/002706512
- Bunch-by-bunch luminosity measurement: 1% offline, 2% online

Tracker
https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2667167

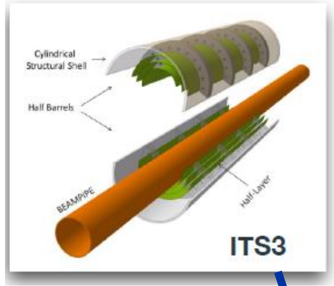
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

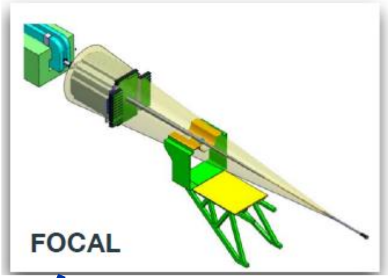
ALICE Future Plans

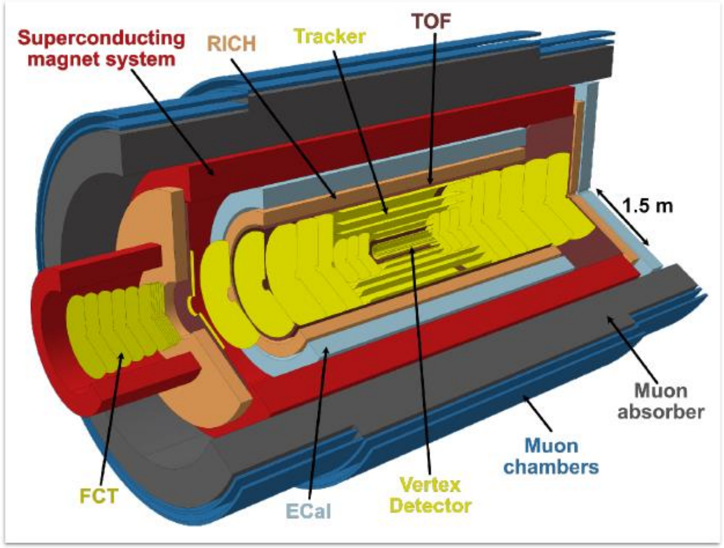
ITS3:
- Replace ITS2 barrel innermost 3 layers
- Reduced inner radius (22 mm → 18 mm)

FOCAL:
- Physics: saturation & shadowing at low x

ALICE 3 (for installation in LS4):
- Compact low-mass all-Si tracker, excellent vertex reconstruction and PID
- Letter of Intent reviewed by LHCC in March
- Discussions with funding agencies started







[CERN-LHCC-2022-009]

LHCb Future Plans

LHCb Upgrade II (for installation in LS4):

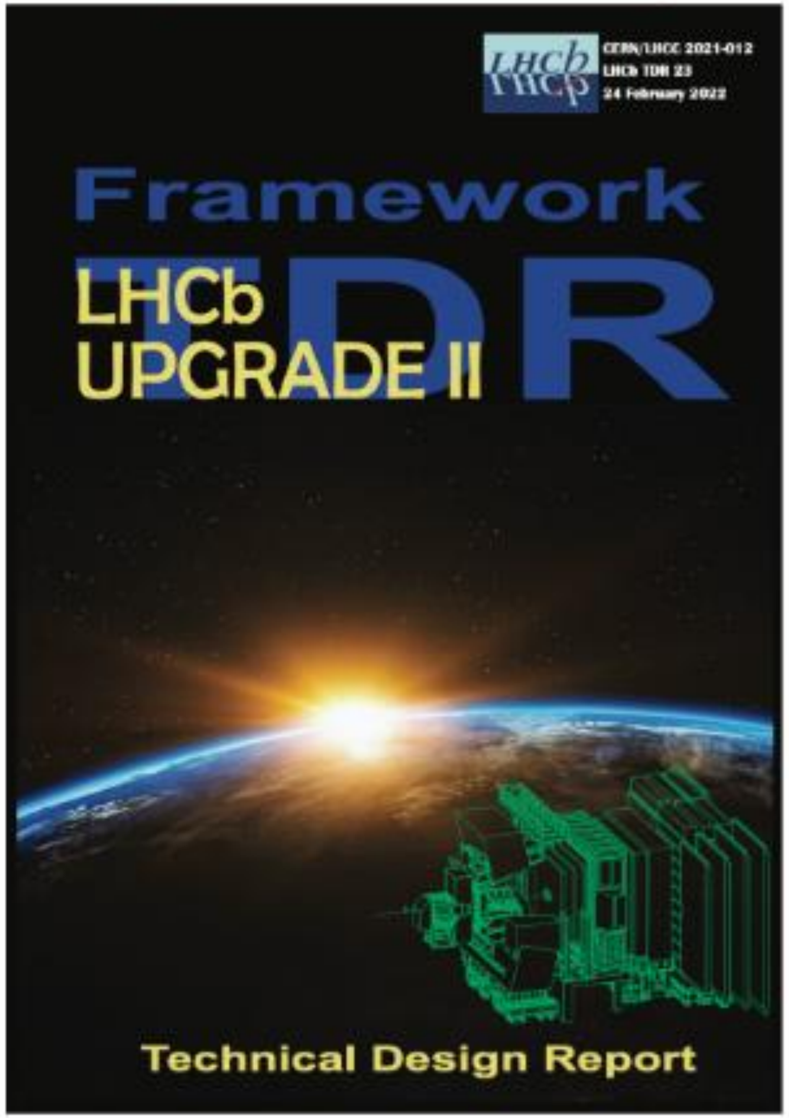
- Fully exploit the HL-LHC for flavour physics
  Ambition:

  $L_{peak} = 1.5\times10^{34}\ cm^{-2}\ s^{-1}$

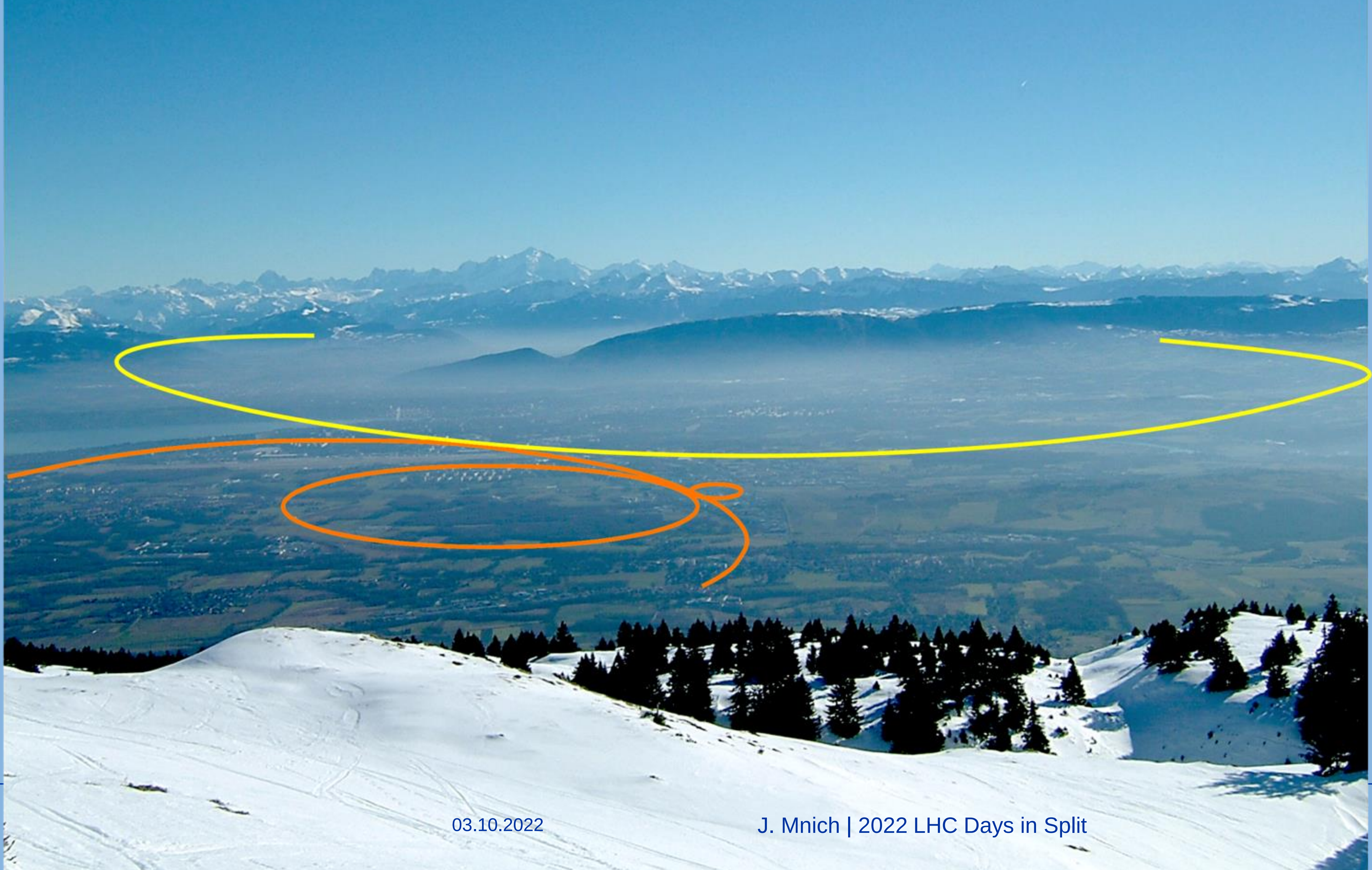
  L_{int} ~ 300 fb^{-1} during Runs 5 & 6

- Targeting same detector performance as in Run 3, but with pile-up ~40!
- New detector technologies (e.g. precision timing, low-cost monolithic pixels)

- Framework TDR reviewed by LHCC in March
- Discussion with funding agencies started



Future Circular Collider (FCC)

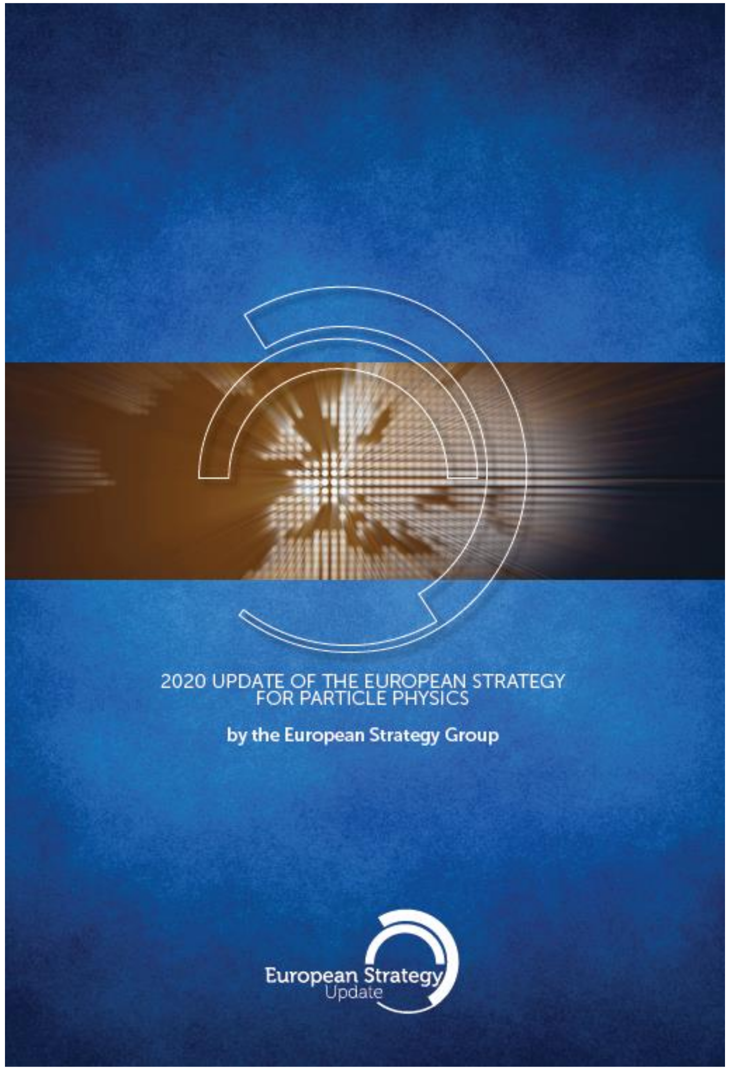


Future Circular Collider (FCC): Feasibility Study

European Strategy for Particle Physics:

- *An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.*
- *"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.*
- *Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."*

CERN has launched the FCC feasibility study to address these recommendations



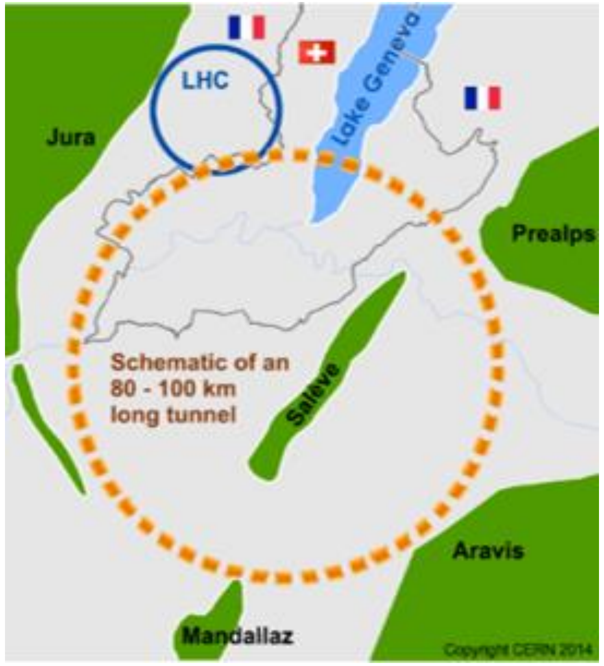
The FCC integrated program inspired by successful LEP – LHC programs at CERN

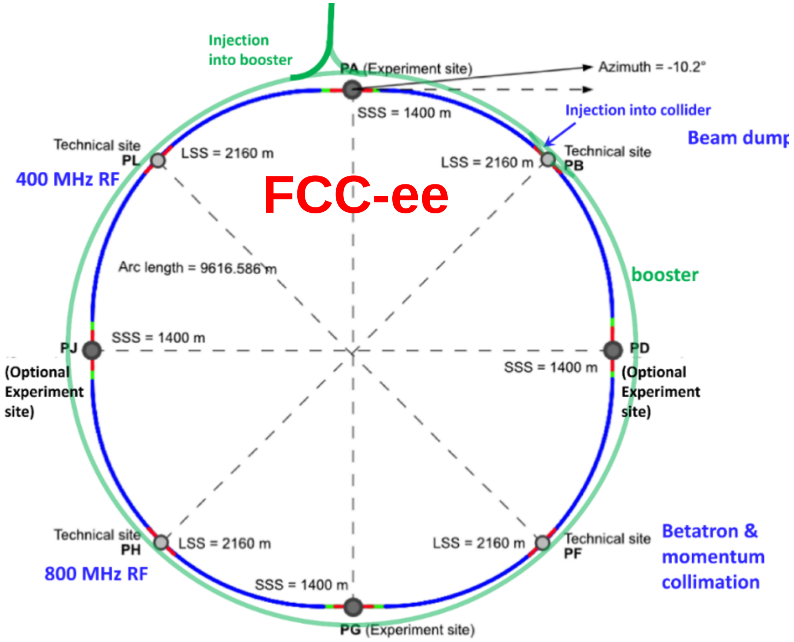
FUTURE CIRCULAR COLLIDER

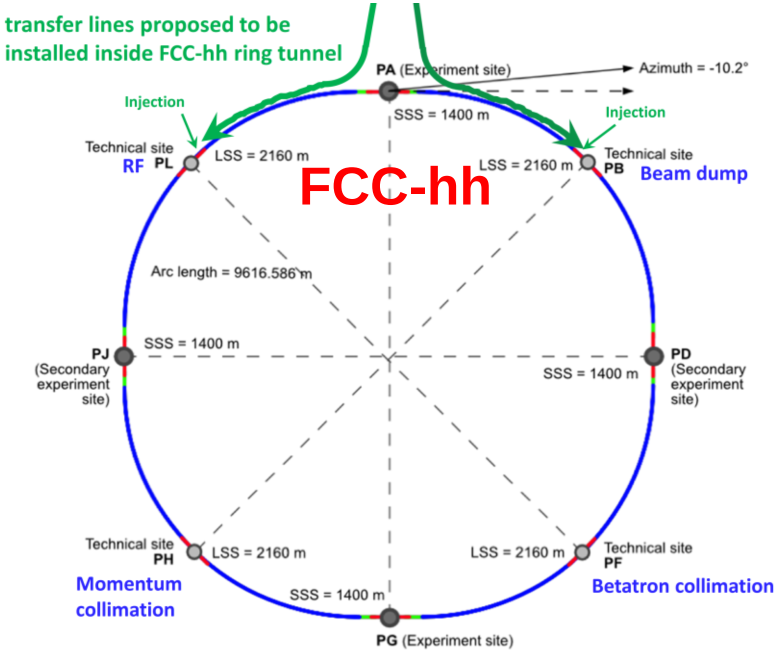
M. Benedikt
April 2022

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program





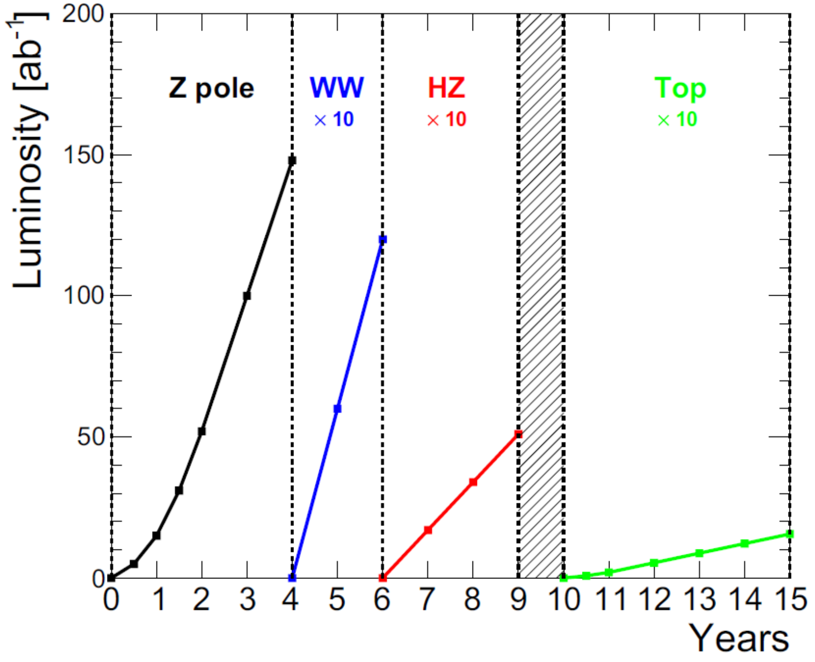


2020 - 2040 | **2045 - 2060** | **2065 - 2090**

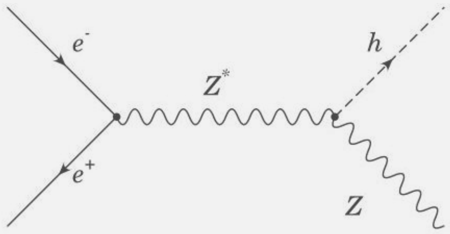
FCC-ee Physics

FCC-ee operation model:

- ❑ Z factory (Tera-Z)
- ❑ WW threshold
- ❑ Higgs factory (≈ 250 GeV cms)
- ❑ Top-pair threshold (→ top mass)

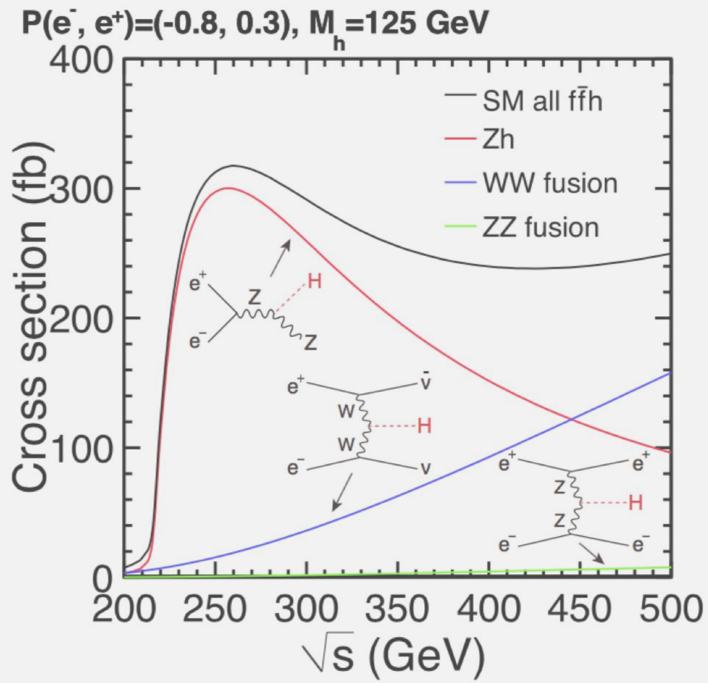


Higgs-strahlungs process at electron-positron Higgs factory:



clean events wrt. LHC

selection through Z decay



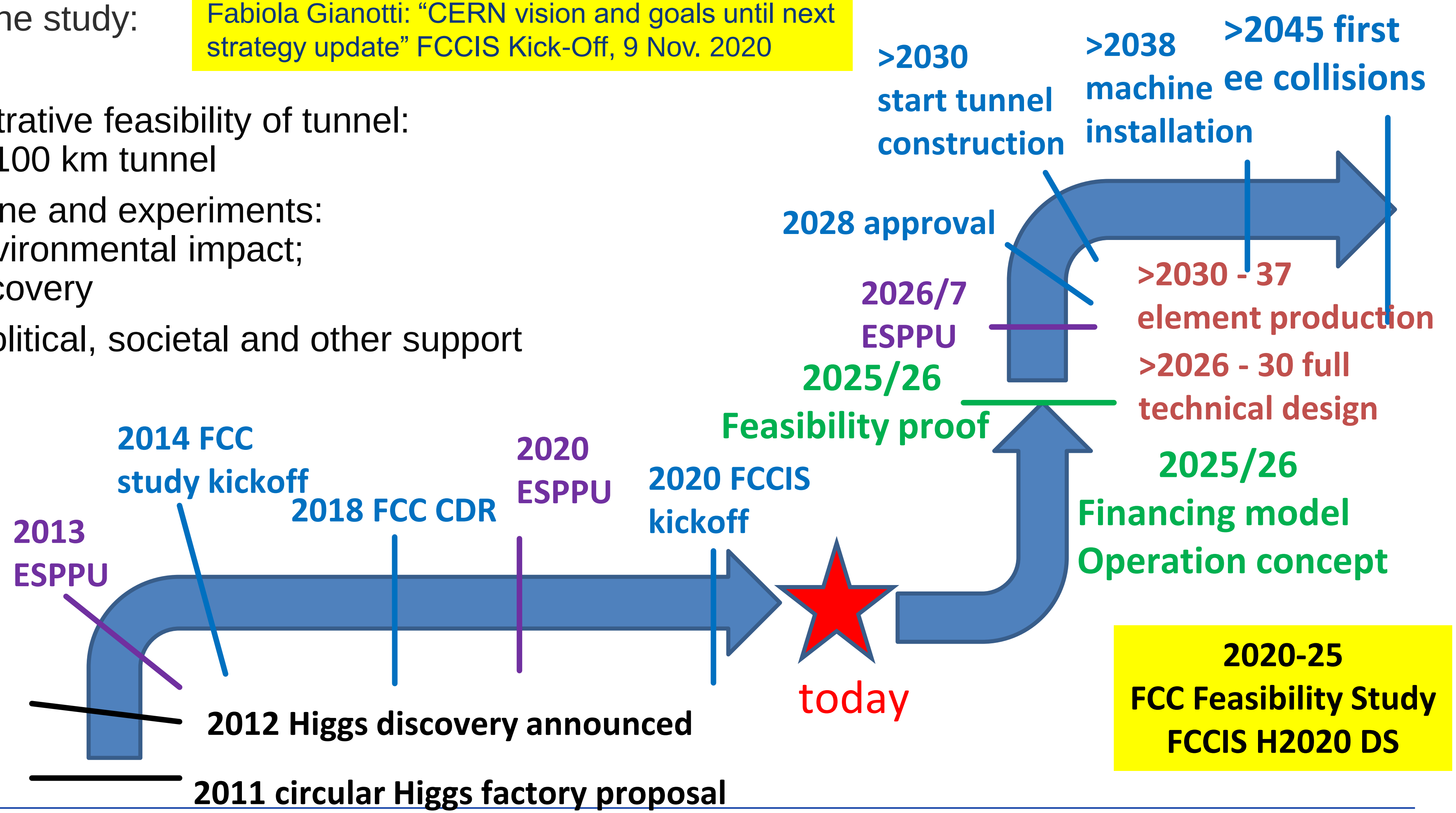
Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^{8} WW events
FCC-ee-H	3	240	5	10^{6} ZH events
FCC-ee-tt	5	345-365	1.5	10^{6} $t\bar{t}$ events

FCC Roadmap Towards First e^+e^- Collisions

Highest priority goals of the study:

- ❑ Financial feasibility
- ❑ Technical and administrative feasibility of tunnel: no show-stopper for ~100 km tunnel
- ❑ Technologies of machine and experiments: magnets; minimise environmental impact; energy efficiency & recovery
- ❑ Gathering scientific, political, societal and other support

Fabiola Gianotti: "CERN vision and goals until next strategy update" FCCIS Kick-Off, 9 Nov. 2020

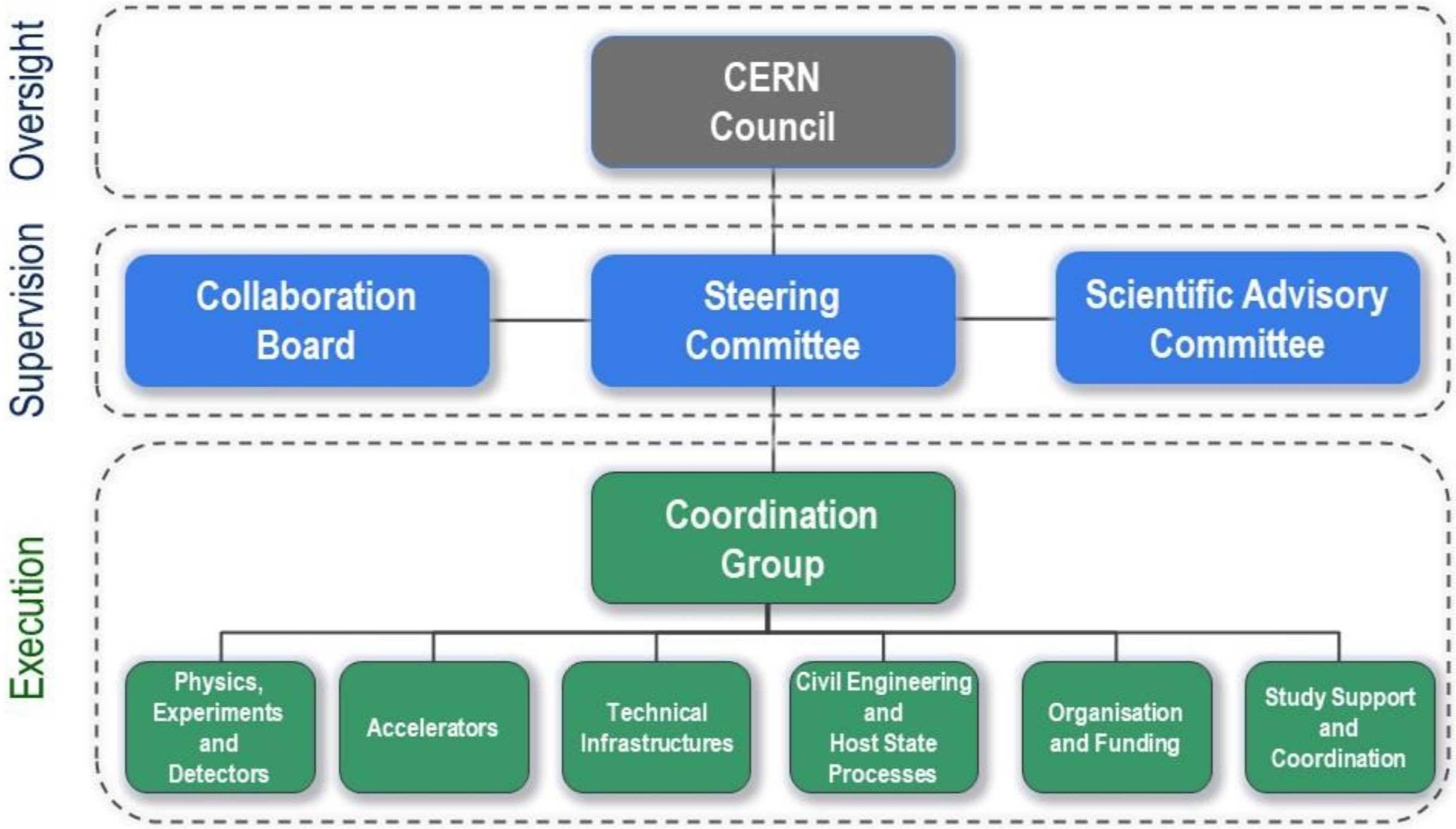


Organisation of the Feasibility Study

Structure unanimously approved by CERN Council in June 2021

A big step forward!

- ❑ Ownership by CERN Council
- ❑ Representatives of the worldwide FCC community
- ❑ Participation of external stakeholders envisaging to make significant financial contributions to possible future project



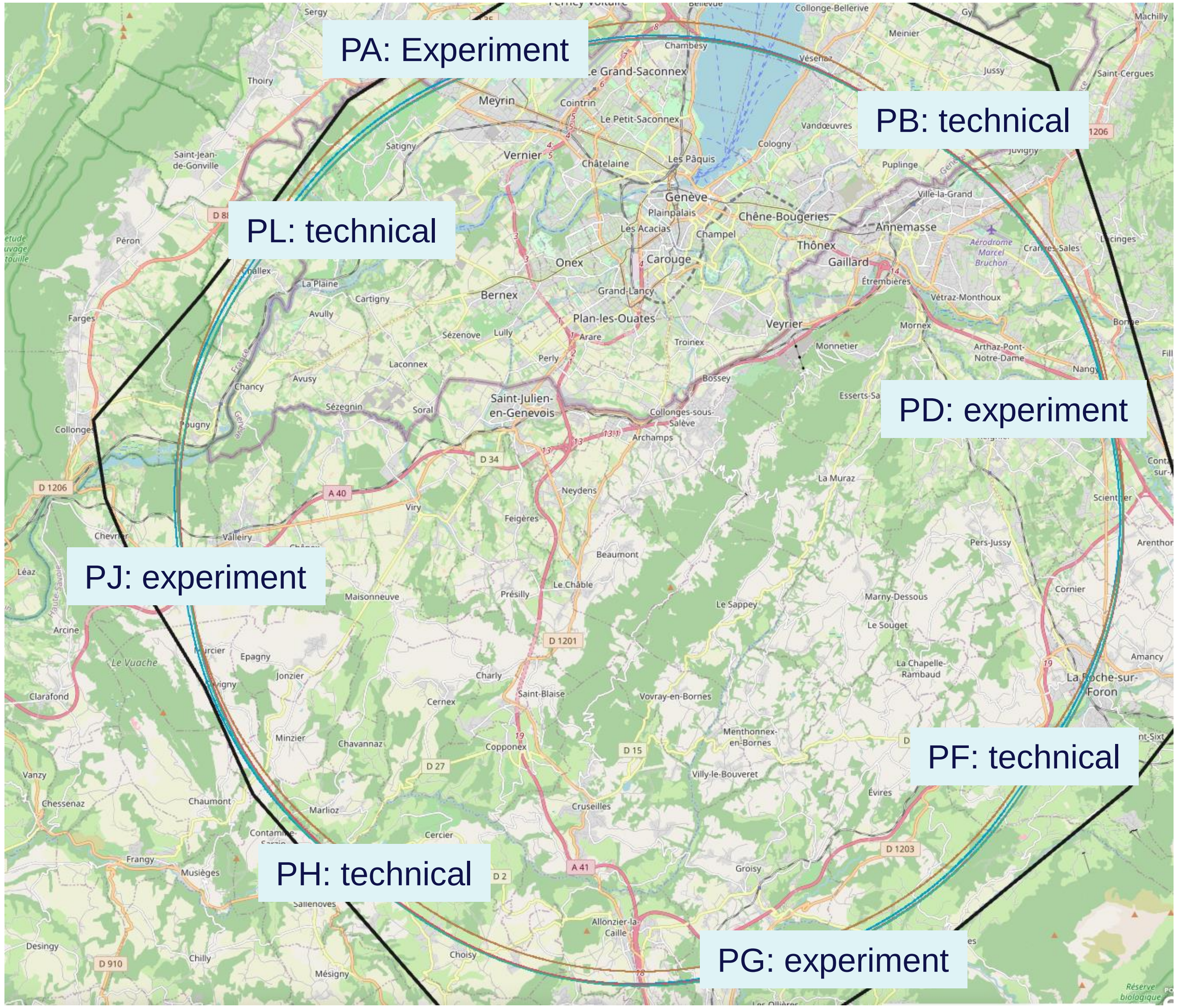
Feasibility study timeline

FCC Feasibility Study

Mid-term review end 2023 regarded
as an important milestone

Deliverables include:

- Infrastructure & placement
- Technical Infrastructure
- Accelerator design FCC-ee and FCC-hh
- Physics, experiments, detectors
- Organisation and financing
- Environmental impact and sustainability studies
- Socio-economic impact

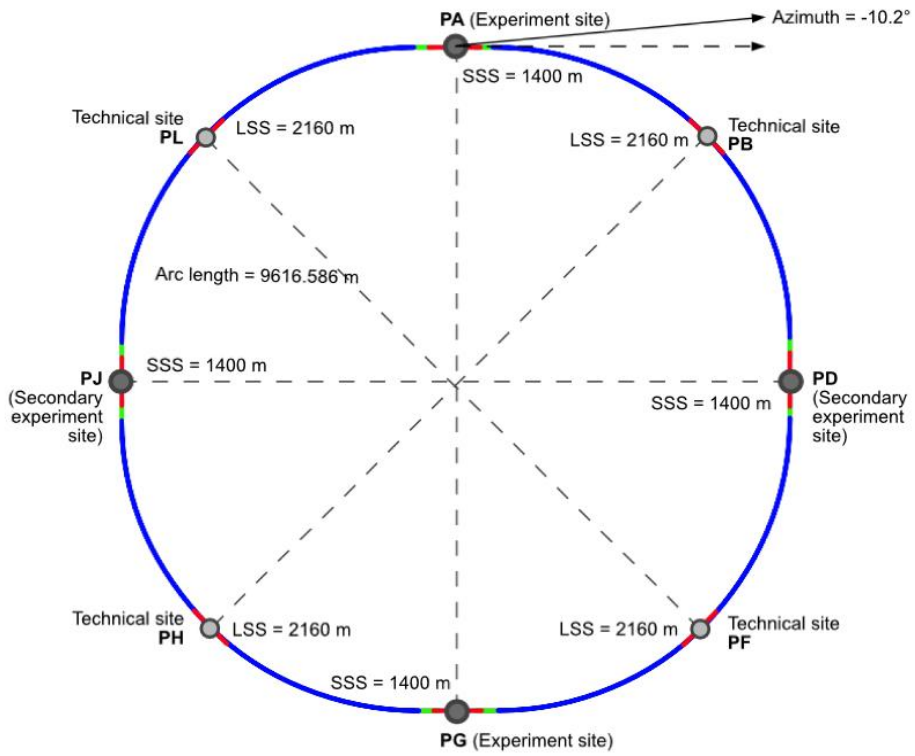


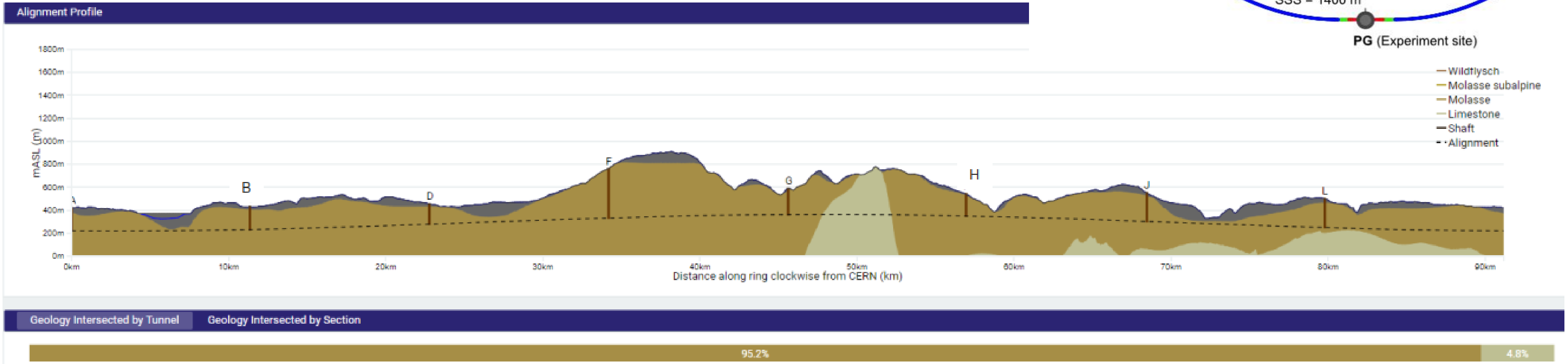
New: “lowest risk” placement

- 8 surface sites
- C = 91.2 km
- 4-fold symmetry and 4-fold superperiodicity
- FCC-ee 2 or 4 IPs
- FCC-hh 4 IPs

Present implementation variant was established considering:

- Geological 3D model and tunnelling risks
- 95% in molasse geology for minimising tunnel construction risks





FCC-hh

How do you get from 14 TeV pp-collisions in LHC to 100 TeV in FCC-hh?

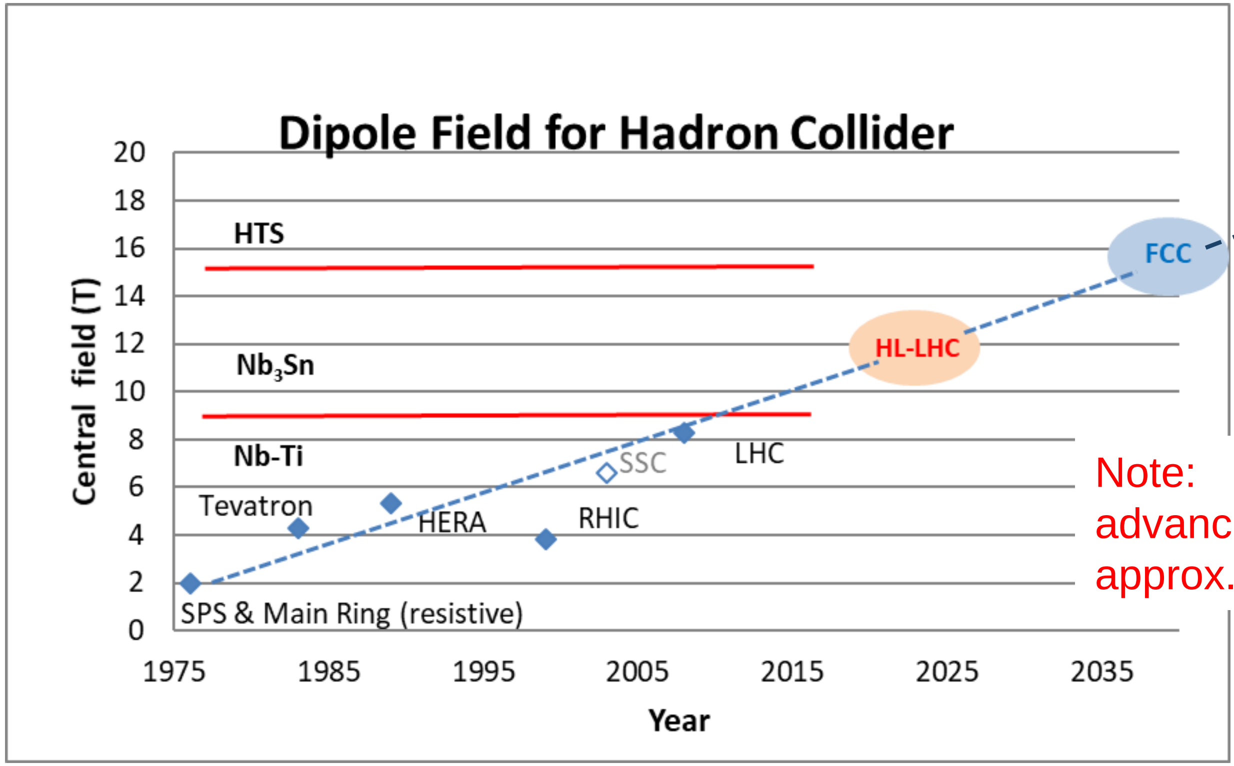
- increase the radius (circumference) by a factor ≈ 3.5 (27 km to 100 km)
- double the dipole field from 8.3 T to ≈ 16 T

Problem:

- with the LHC the well established Nb-Ti technology (HERA, Tevatron, RHIC, …) comes at its physical limits

R&D high magnet needs to be pushed!

- as well for alternative colliders at the energy frontier



20 T in ≥ 2050?

Note:
advancement in dipole field approx. ≈ +2 T per decade!

Statement from the Strategy update:

The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities..

Status of Global FCC Collaboration

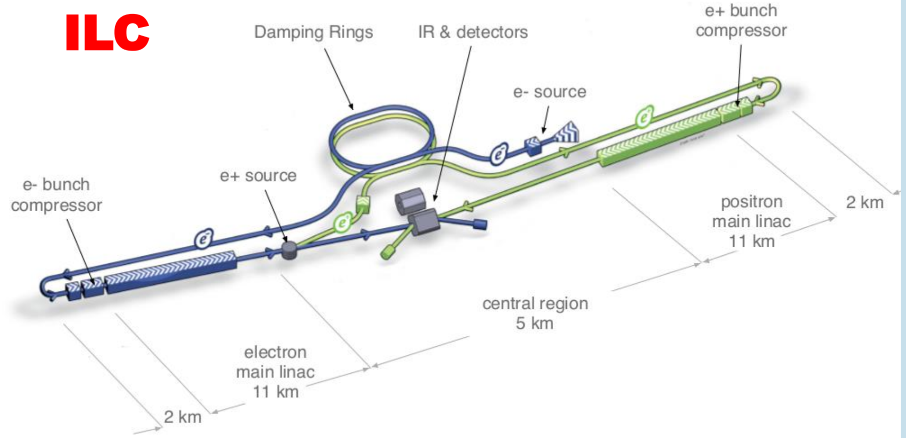
Increasing international collaboration as a prerequisite for success:

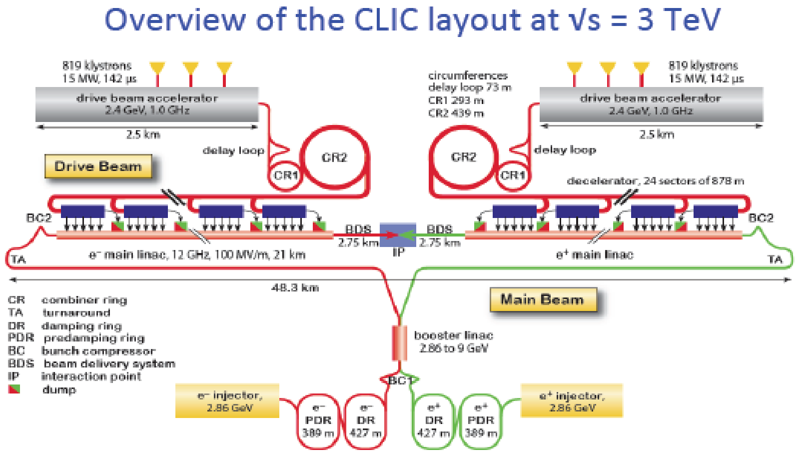
links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

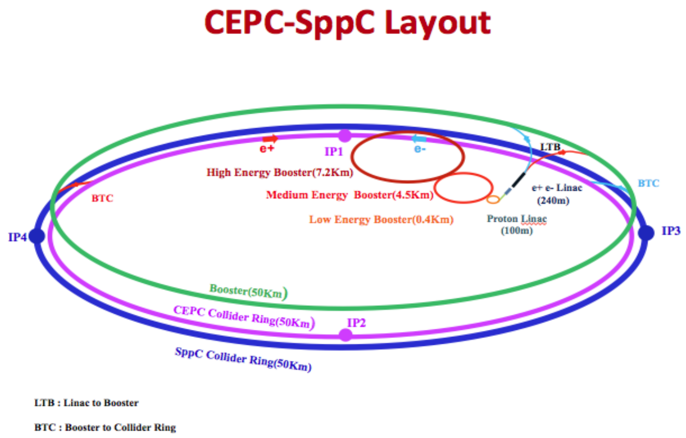
Other studies on Higgs factories

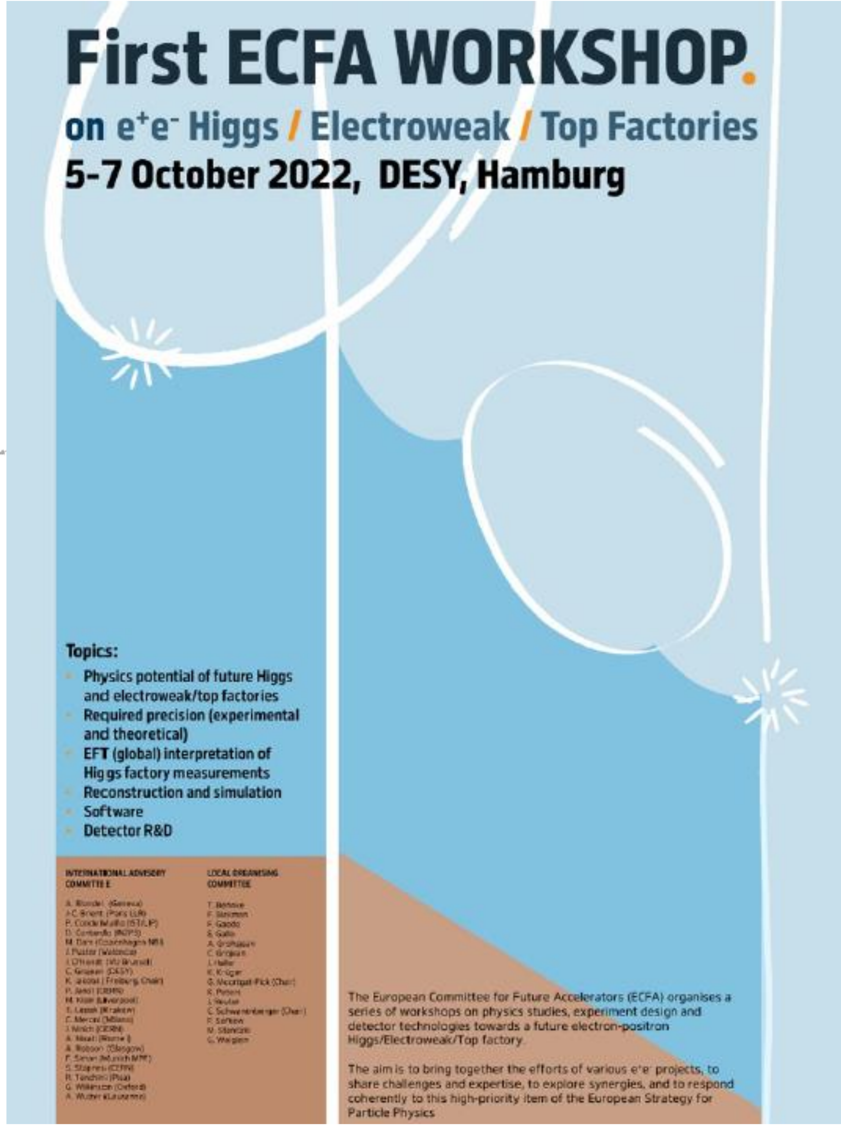
FCC-ee is not the only idea/study for a Higgs factory

- ILC (Japan, or elsewhere?)
- CLIC
- CEPC (China)
- New:
  Cool Copper Collider (USA)









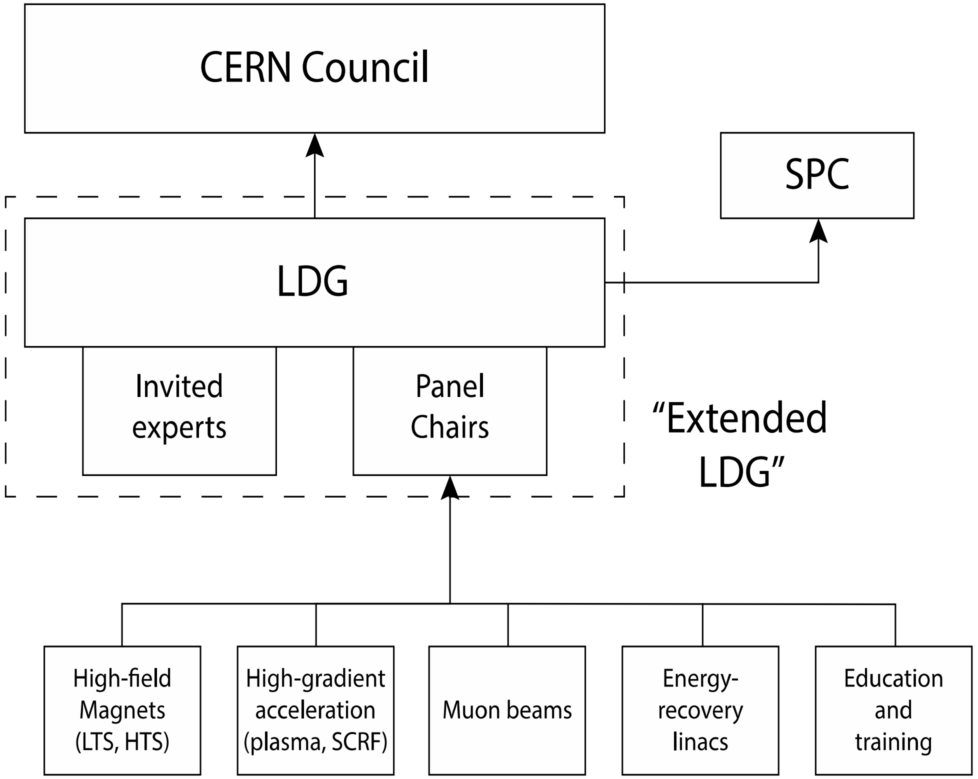
Accelerator Roadmap

CERN and the national laboratories in Europe (LDG) are charged by CERN Council to define a Roadmap for Accelerator R&D

Topics:

- High-field magnets
- High-gradient accelerations (plasma, SCRF)
- Muon beams/collider
- Energy recovery linacs
- Education and training

Goal: be able at the next strategy update to identify viable options which deserve to be pursued



Roadmap presented to Council end of 2021
Key importance for a successful execution of the roadmap: collaboration between labs and universities in Europe and beyond

Accelerator R&D at CERN

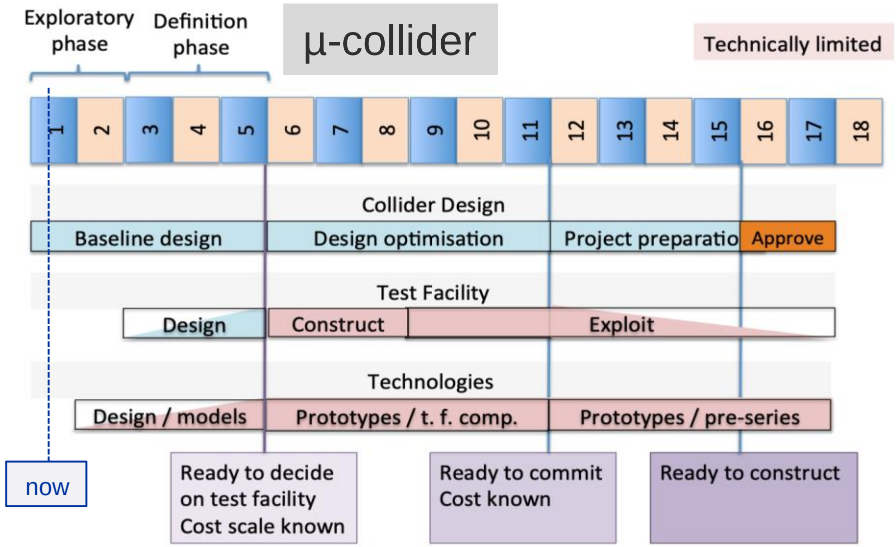
In addition to the high-field magnet programme (part of FFC study)

- ❑ Continue CLIC study to prepare for next strategy update
  - ❑ finalize X-band technology towards construction readiness
  - ❑ improve power efficiency (klystrons)
  - ❑ project readiness report by end 2025

- ❑ Muon collider
  - ❑ work on main challenges:
    muon source, cooling, fast ramping magnets, accelerator, collider ring, neutrino bkgd, civil engineering
  - ❑ for next strategy: is investment into μ-collider test facility justified?

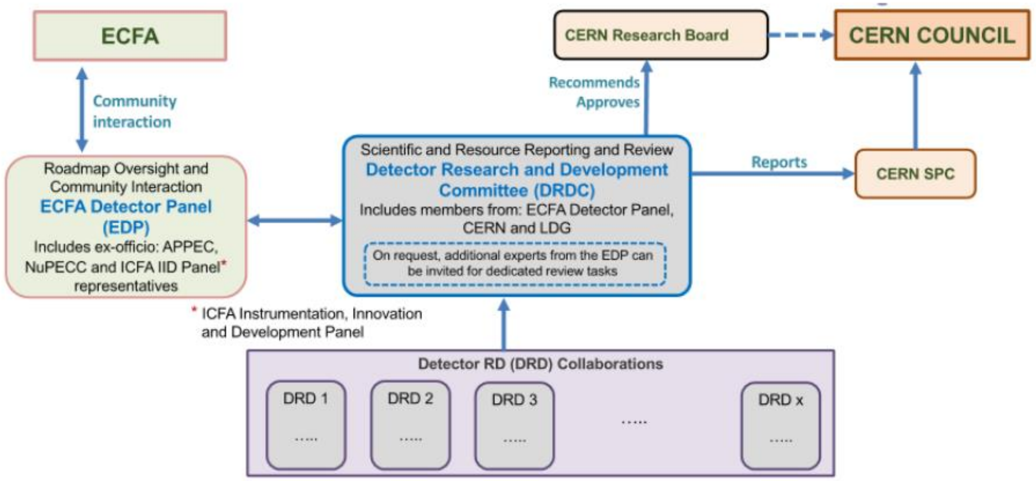
CLIC

Parameter	Unit	Stage 1	Stage 2	Stage 3
√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 √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



ECFA Detector R&D Roadmap Panel

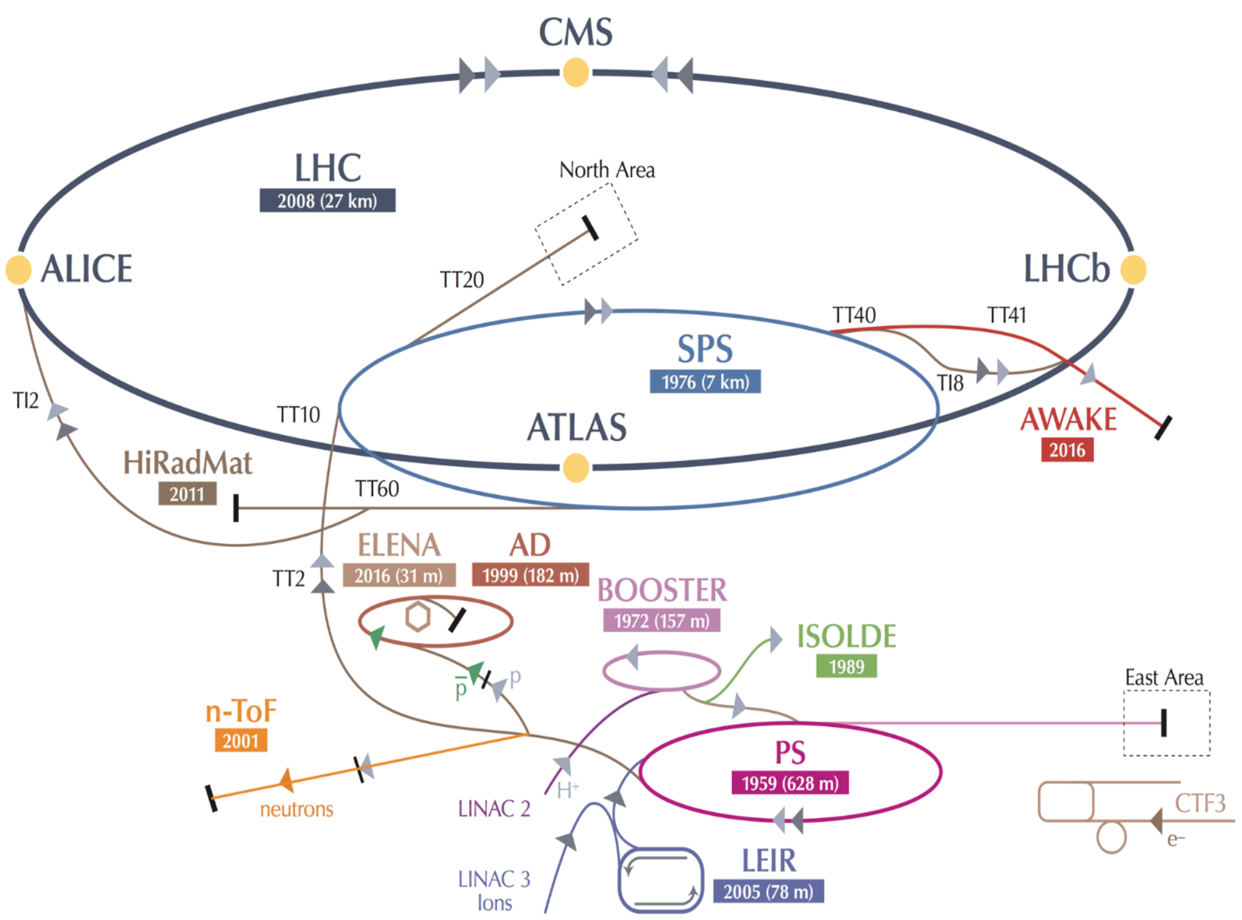
CERN Council has charged European Committee for Future Accelerators (ECFA) to define a Detector R&D Roadmap



Detector R&D (DRD) Collaborations are being set up on:
Gaseous Detectors, Liquid Detectors, Solid State Detectors,
Photon Detector & PID, Quantum & Emerging Technologies, Calorimeter

Electronics, Integration, Training
Start: January 2024

CERN Diversity Programme



~20 projects other than LHC with > 1200 physicists

- **AD: Antiproton Decelerator for antimatter studies**
- **AWAKE: proton-induced plasma wakefield acceleration**
- **CAST, OSQAR: axions**
- **CLOUD: impact of cosmic rays on aeorosols and clouds → implications on climate**
- **COMPASS: hadron structure and spectroscopy**
- **ISOLDE: radioactive nuclei facility**
- **LHC**
- **NA61/Shine: ions and neutrino targets**
- **NA62: rare kaon decays**
- **NA63: radiation processes in strong EM fields**
- **NA64: search for dark photons**
- **Neutrino Platform: ν detector R&D for experiments in US, Japan**
- **n-TOF: n-induced cross-sections**
- **UA9: crystal collimation**

Future of the diversity programme discussed in the Physics Beyond Collider study

Summary

Priorities for particle physics and CERN are defined by the 2020 European Strategy:

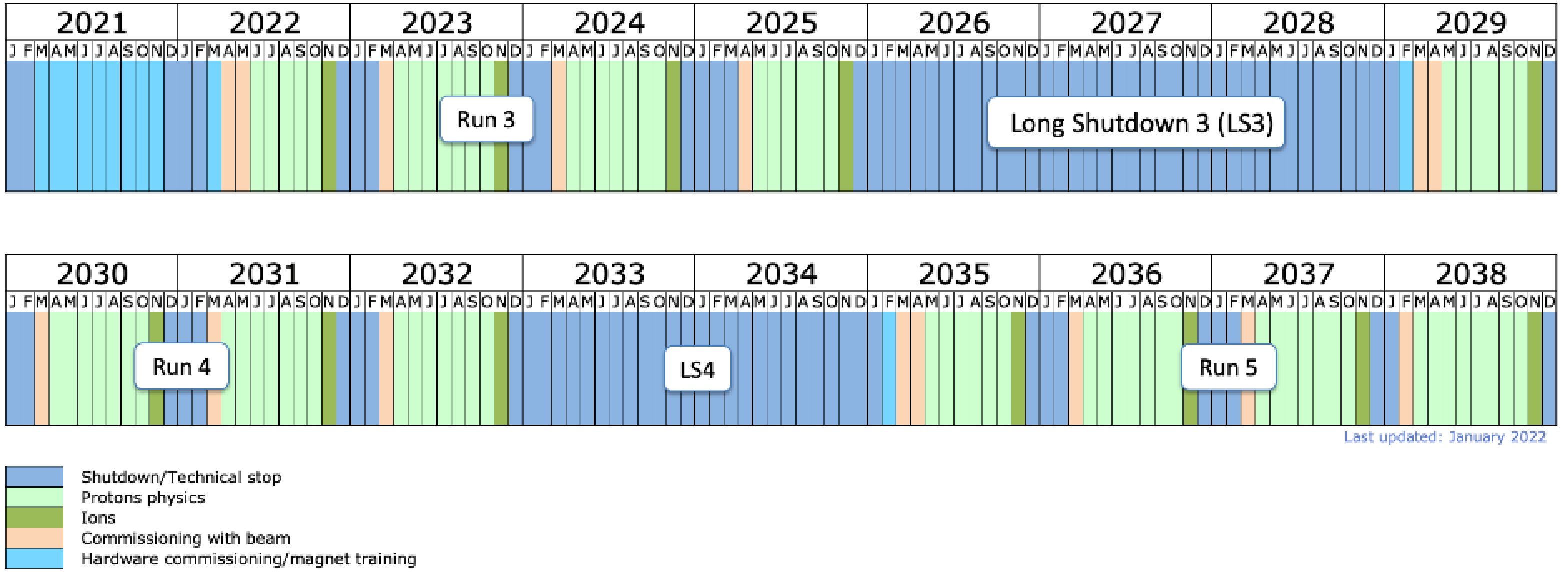
- ❑ Full scientific exploitation of the LHC
  - ❑ Programme defined until around 2040+ and includes upgrades of the accelerator (HL-LHC) and the detectors
- ❑ Next global project:
  - ❑ Electron-positron Higgs (and EW) factory to study this very special particle to highest precision
  - ❑ Ambition for an 100 TeV hadron collider significantly extending the reach of the LHC
  - ❑ CERN launched the FCC feasibility study as global project
    Perspective for a scientific programme until the end of this century!
- ❑ Need a clear idea of the project at the next strategy update
- ❑ R&D on accelerator and detectors, incl. training of young talents, is mandatory

Backup Slides

LHC: From the Idea to its Realisation

around 1980:	First ideas for a muli-TeV proton collider at CERN
Oct 1990:	ECFA LHC Workshop in Aachen
16 Dec 1994:	CERN Council approved the LHC project
Feb 1996:	Approval ATLAS and CMS
Apr 1998:	Begin of construction
7 Mar 2005:	Installation of the first dipole magnet
26 Apr 2007:	Installation of the last dipole magnet
10 Sep 2008:	First circulating proton beams
Okt 2009:	First proton-proton collisions
Jul 2012:	Discovery of the Higgs
2029:	Begin High Luminosity Phase (HL-LHC)
around 2040:	Envisaged end of the scientific programme

HL-LHC

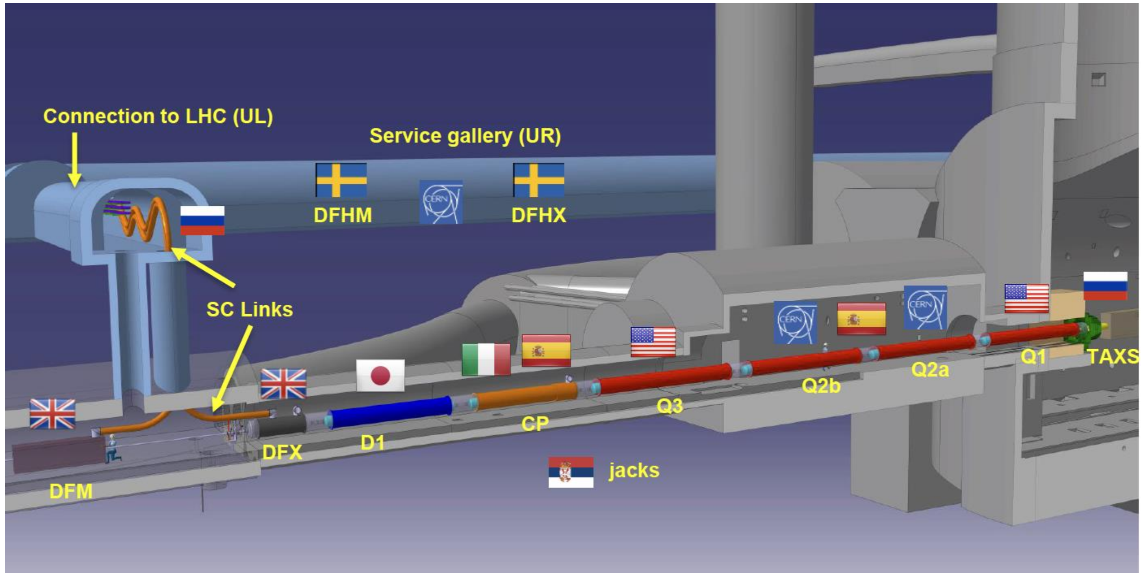


New schedule released early 2022

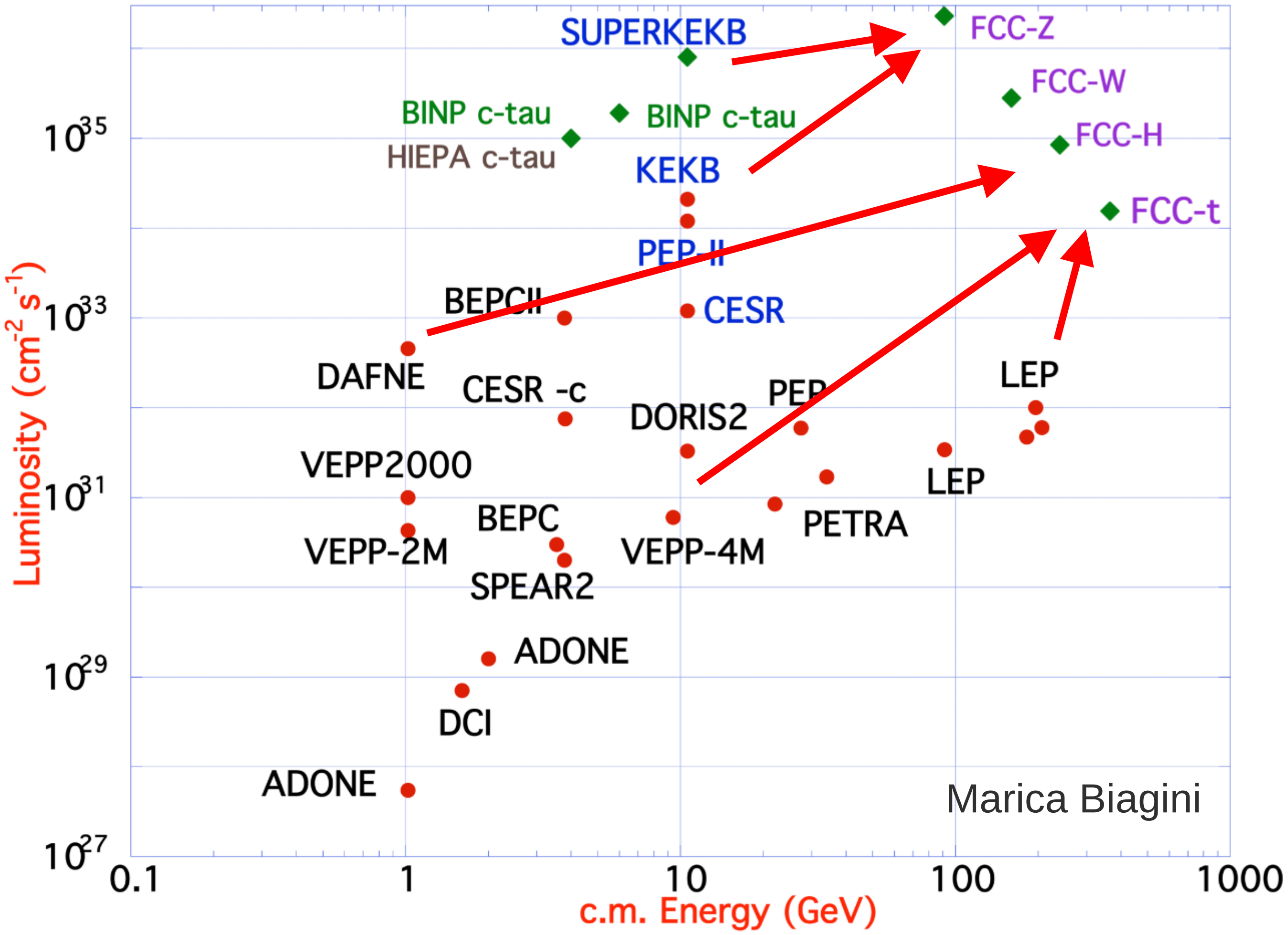
- Extension of Run 3 until end 2025
- Extension LS3 by ½ year to end 2028

Accelerator:

- Good progress in 2021/22 on all fronts despite COVID-19
- Completion of prototypes and start of series production for many components
- 2022 is a crucial year:
  - Production phase, resolution of important technical issues to be confirmed
  - Procurement (& in-kind contributions) in very challenging global market conditions
  - Plan B for in-house production of Russian in-kind contributions being fully developed



FCC-ee Design Concept

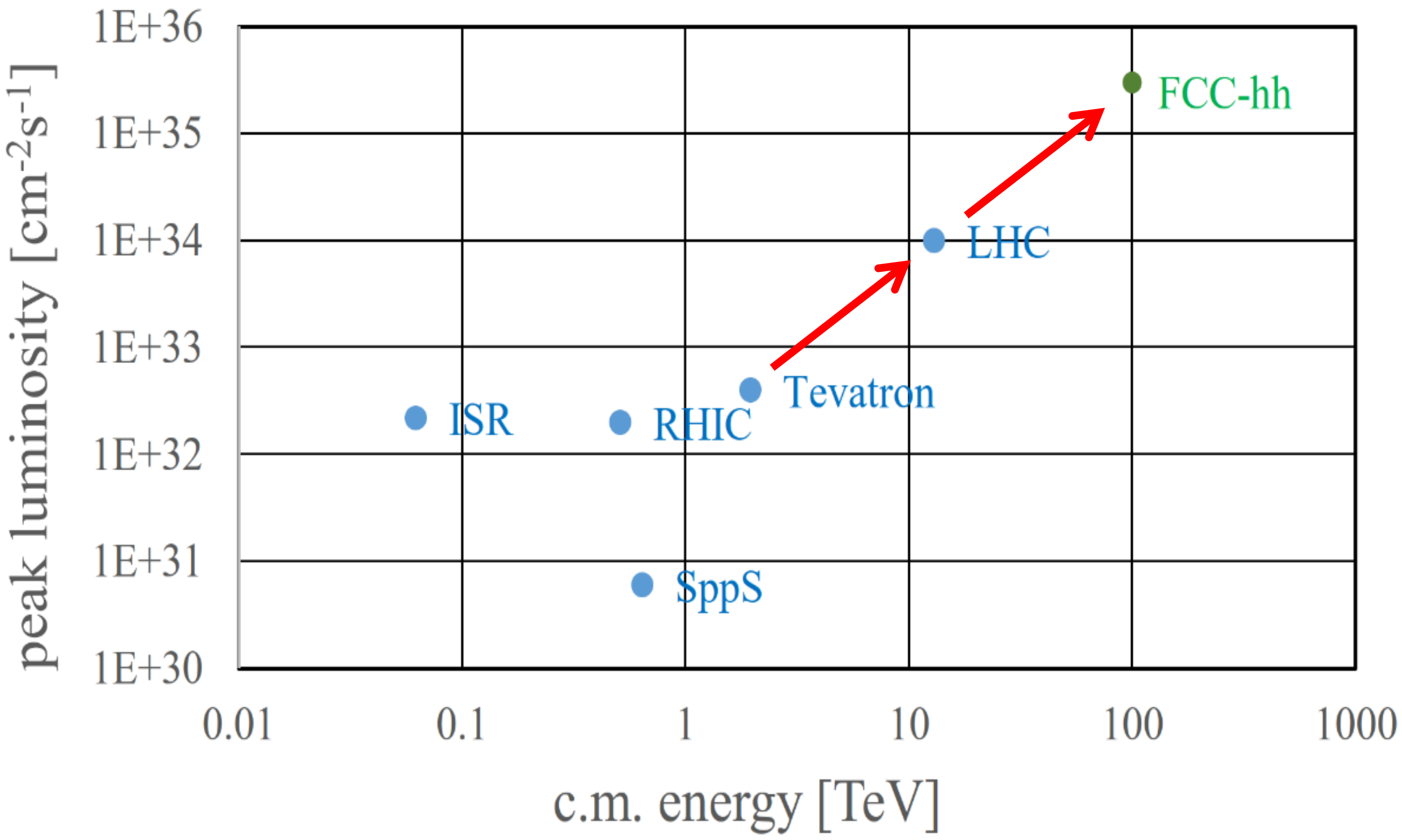


Based on lessons and techniques from past colliders (last 40 years)

- B-factories: KEKB & PEP-II:
  - double-ring lepton colliders,
  - high beam currents,
  - top-up injection
- DAFNE: crab waist, double ring
- S-KEKB: low by*, crab waist
- LEP: high energy, SR effects
- VEPP-4M, LEP: precision E calibration
- KEKB: e^+ source
- HERA, LEP, RHIC: spin gymnastics

Combining successful ingredients of several recent colliders → highest luminosities & energies

FCC-hh: Highest Collision Energies

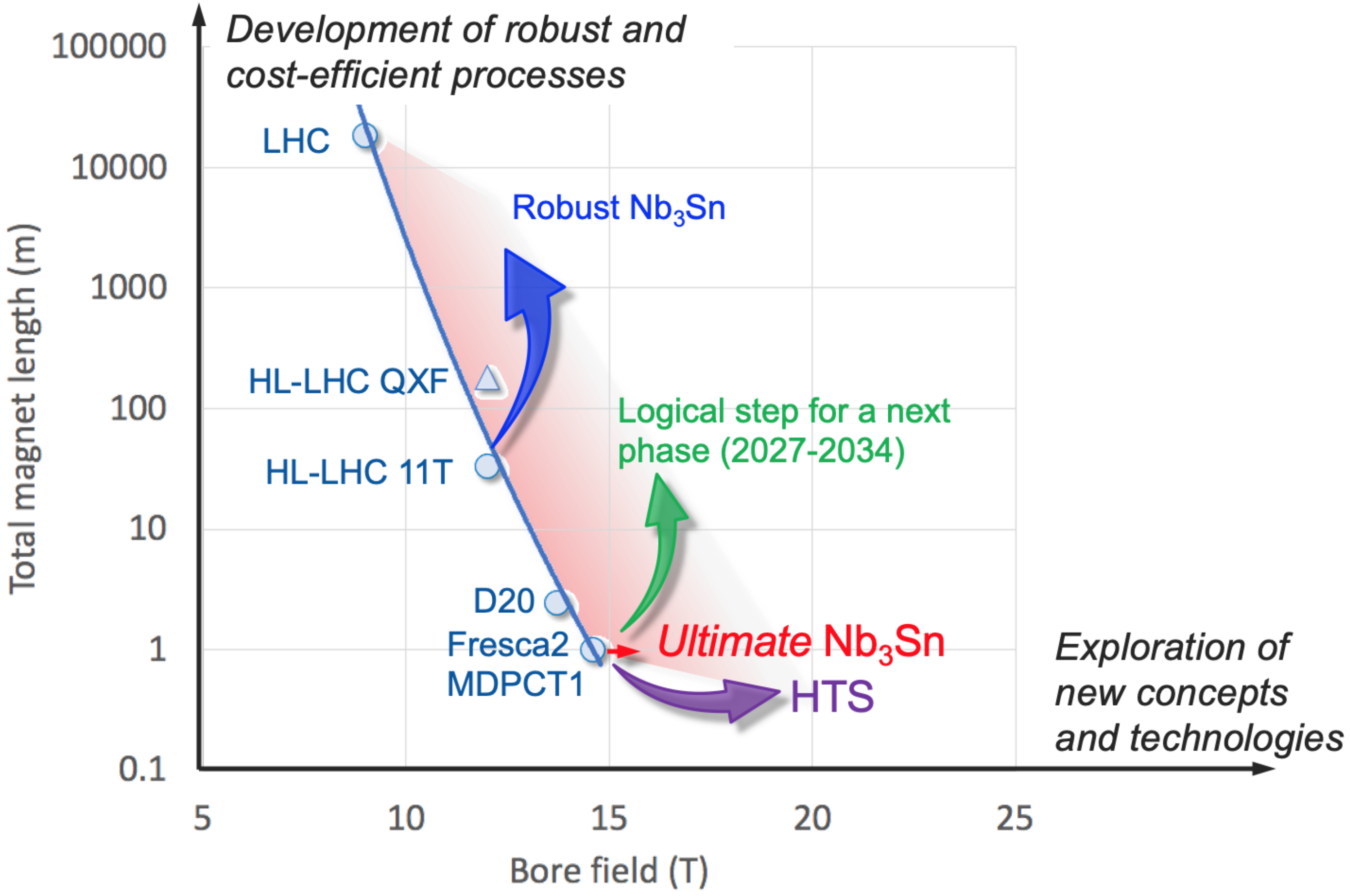


Key challenges:

- Order of magnitude performance increase in both energy & luminosity
- 100 TeV cm collision energy (vs 14 TeV for LHC)
- 20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)
- Similar performance increase as from Tevatron to LHC
- Key technology: high-field magnets

R&D on High-Field Magnets

In parallel to FCC Study, HFM development program as long-term R&D project

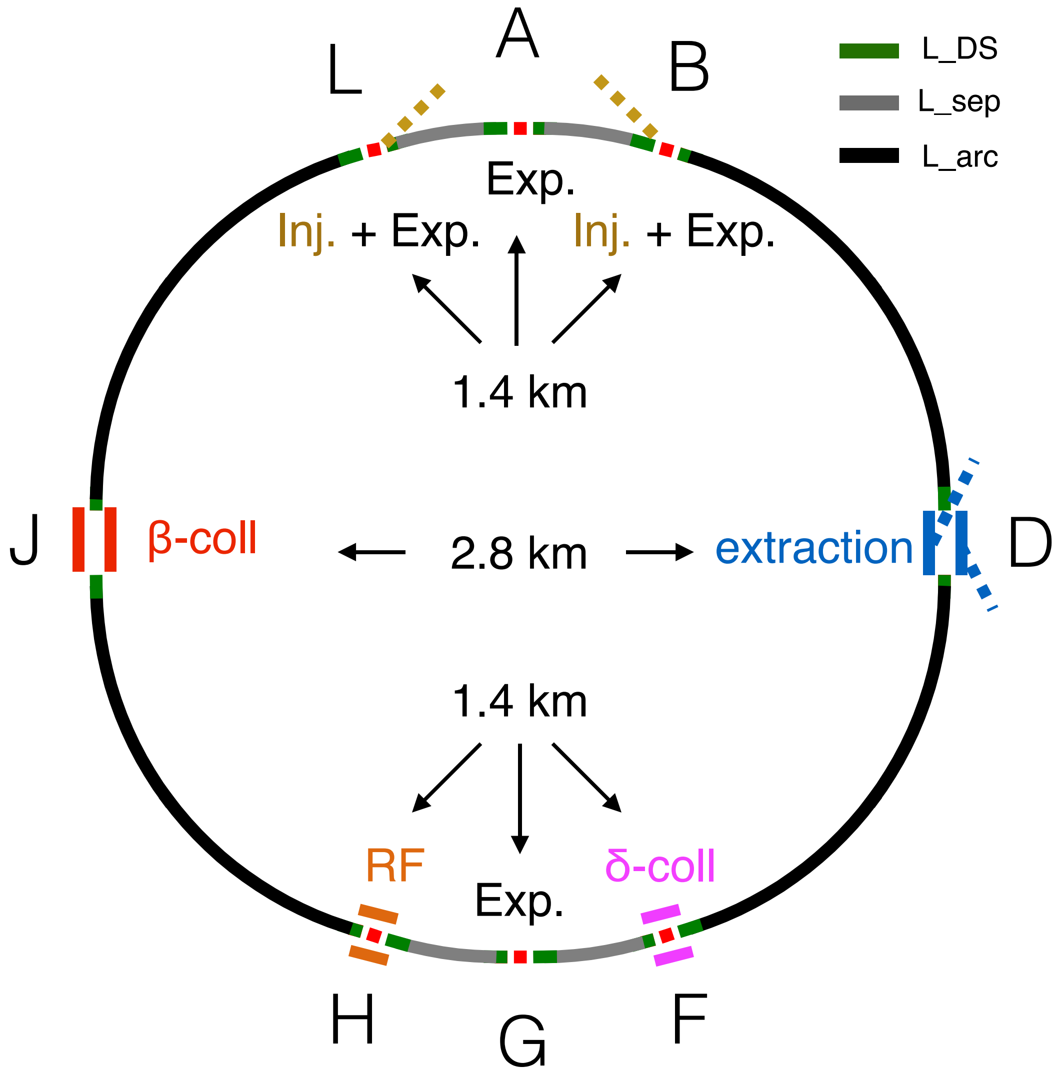


Main R&D activities:

- ❑ Materials: goal is ~16 T for Nb_3Sn, at least ~20 T for HTS inserts
- ❑ Magnet technology: engineering, mechanical robustness, insulating materials, field quality
- ❑ Production of models and prototypes: to demonstrate material, design and engineering choices, industrialisation and costs
- ❑ Infrastructure and test stations: for tests up to ~ 20 T and 20-50 kA

Global collaborations already established during FCC CDR phase.

FCC-hh Basic Design Choices



- ❑ Dual aperture superconducting magnets
- ❑ Two high-luminosity experiments (A & G)
- ❑ Two other experiments (L & B) combined with injection upstream of experiments
- ❑ Two collimation insertions
  - ❑ Betatron cleaning (J)
  - ❑ Momentum cleaning (F)
- ❑ Extraction/dump insertion (D)
- ❑ RF insertion (H)
- ❑ Injection from LHC (~3 TeV) or scSPS (~1.2 TeV)
- ❑ Alternative layouts under study

FCC-ee Physics Program Staging

working point	luminosity/IP $[10^{34}\ cm^{-2}s^{-1}]$	total luminosity (2 IPs)/ yr	physics goal	run time [years]
Z first 2 years	100 (50% nominal)	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	48 ab^{-1}/year		
W	25	6 ab^{-1}/year	10 ab^{-1}	2
H	7.0	1.7 ab^{-1}/year	5 ab^{-1}	3
machine modification for RF installation & rearrangement: 1 year				
top 1st year (350 GeV)	0.8 (50% nominal)	0.2 ab^{-1}/year	0.2 ab^{-1}	1
top later (365 GeV)	1.4	0.34 ab^{-1}/year	1.5 ab^{-1}	4

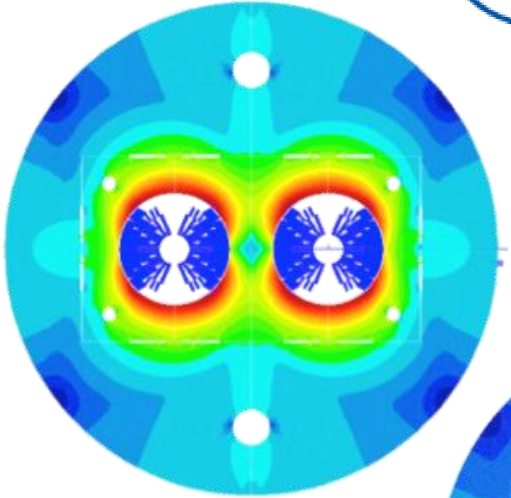
Total program duration: 15 years - including machine modifications

- Phase 1 (Z, W, H): 9 years,
- Phase 2 (top): 6 years

16 T dipole design activities and options

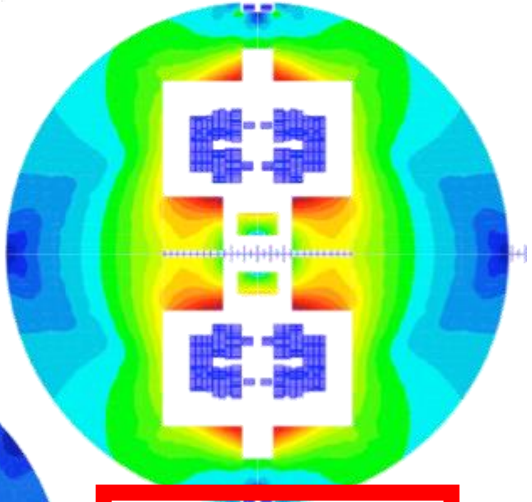
H2020

Cos-theta



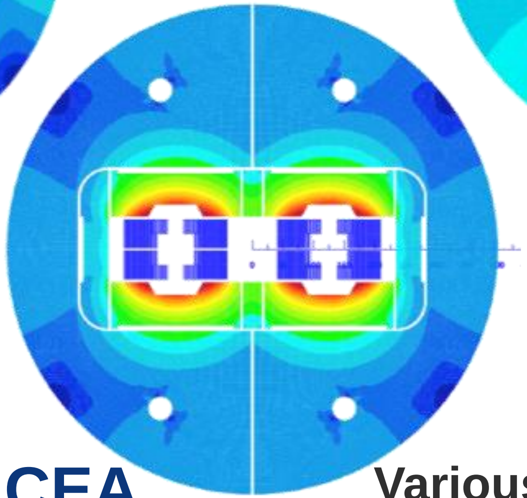
INFN

Common coils



CIEMAT

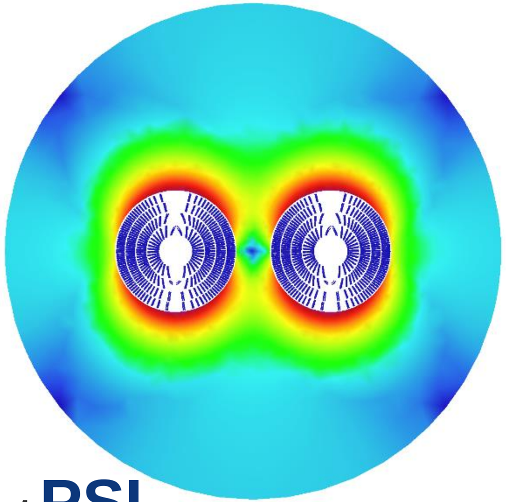
Blocks



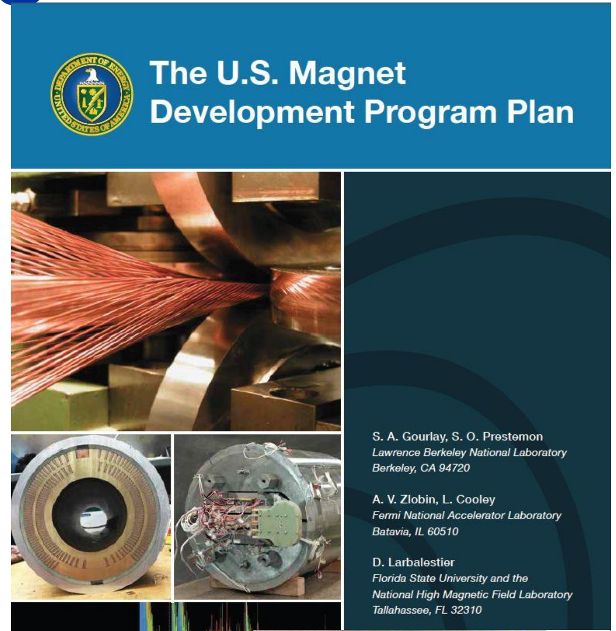
CEA

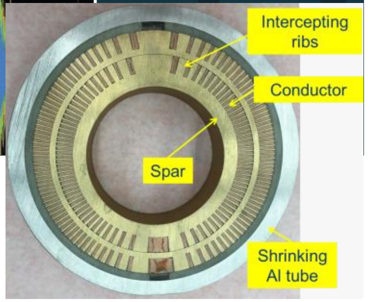
Swiss contribution

Canted
Cos-theta



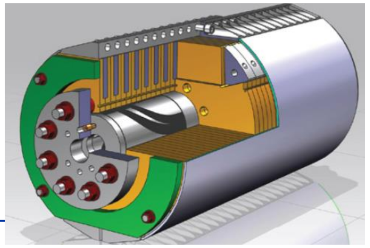
PSI





LBNL

FNAL



Various programs on short model magnets ongoing

FCC-hh (pp) Collider Parameters

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	~16		8.33	8.33
circumference [km]	91.2		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]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		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]	8.4		0.7	0.36

Physics Beyond Collider Study

PBC is an exploratory study launched in 2016 aimed at exploiting the full scientific potential of CERN's accelerator complex and its scientific infrastructure

http://pbc.web.cern.ch/

- complementary to LHC and other high-energy colliders
- target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders

Provided in put to the ESPP

- PBC Summary Report: arXiv:1902.00260

Study will continue

- workshop March 2021
- https://indico.cern.ch/event/1002356/

Topics include:

- ❑ LHC injectors:
- ❑ Low energy facilities
- ❑ High energy fixed target
- ❑ Other opportunities gamma-factory
- ❑ nuSTORM @CERN
- ❑ Precision measurement and rare decays
- ❑ High energy beam dumps
- ❑ Low energy hidden sector (axions, EDM)
- ❑ QCD and HI

Study leaders:
Joerg Jaeckel (Heidelberg)
Mike Lamont (CERN) → Gianluigi Arduini
Claude Vallee (Marseille)

10th Anniversary of Higgs Boson Discovery

On 4 July 2022, CERN marks 10 years since the ATLAS and CMS experiments announced the discovery of the Higgs boson

Centrepiece was a full-day scientific symposium in CERN's main auditorium celebrating the discovery, give an overview of what's been learned since then, and take a look forward at what's still to come

https://indico.cern.ch/event/1135177/

FCC Stage 1: Infrastructure and FCC-ee Project Cost Estimate

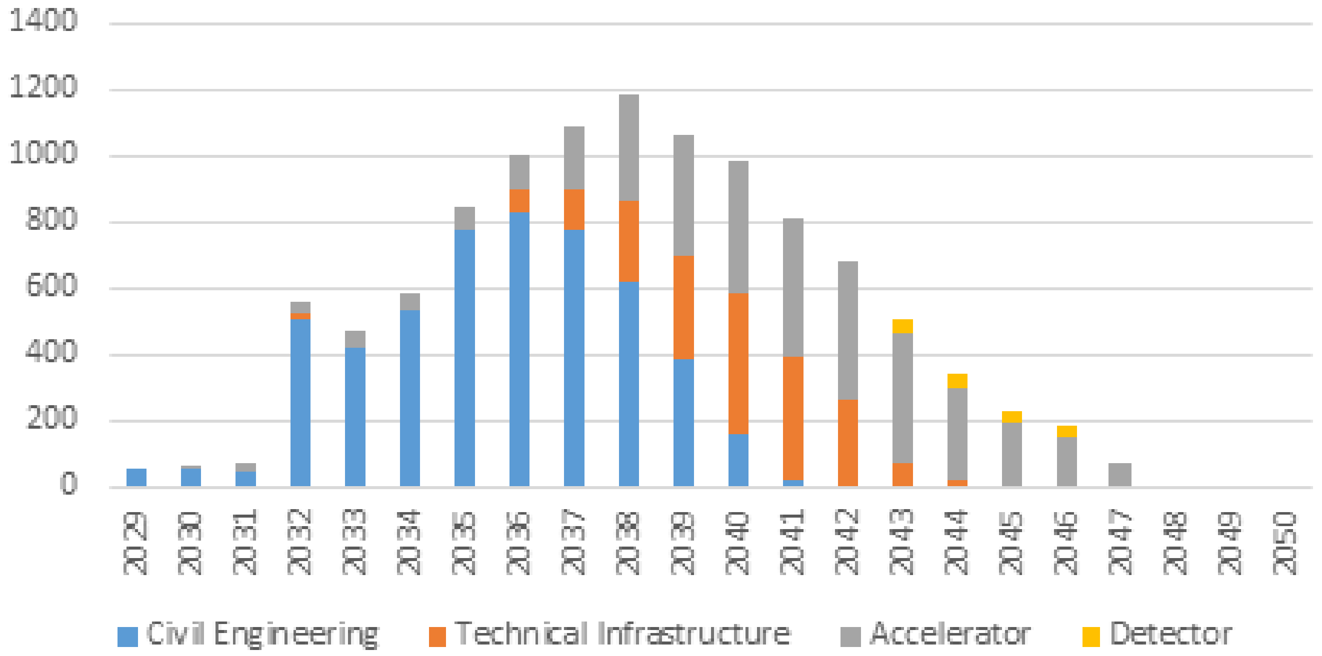
Construction cost estimate for FCC-ee

- Machine configurations for Z, W, H working points included
- Baseline configuration with 2 detectors
- CERN contribution to 2 experiments incl.

cost category	[MCHF]	%
civil engineering	5.400	50
technical infrastructure	2.000	18
accelerator	3.300	30
detector	200	2
total cost (2018 prices)	10.900	100

Spending profile for FCC-ee

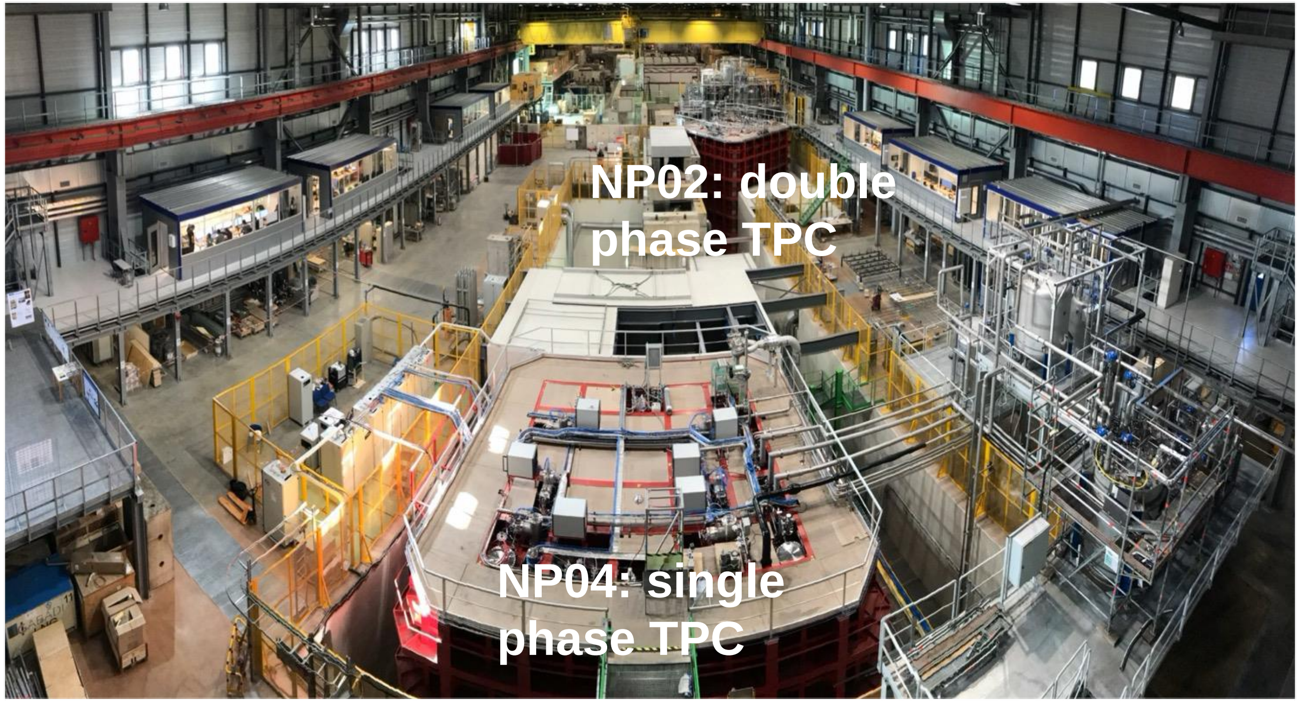
- Civil engineering construction 2032 - 2040
- Technical infrastructure 2037 - 2043
- Accelerator and experiment 2032 – 2045
- Commissioning and operation start 2045 -2048.



Neutrino Physics

Europe, and CERN through the Neutrino Platform, should continue to support long baseline experiments in Japan and the United States.

Following the 2013 strategy update CERN operates the Neutrino Platform (NP) to support European researchers participating in long-baseline neutrino experiments elsewhere



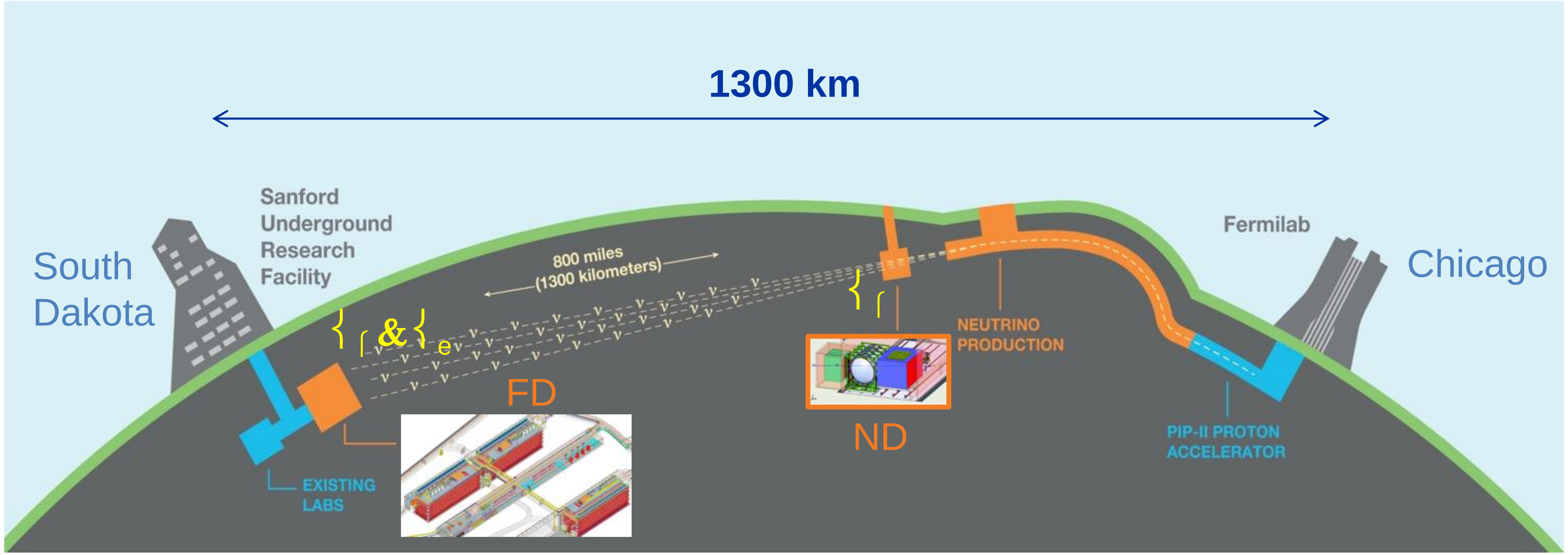
Examples of CERN contributions:

- development of LAr TPC for DUNE (ProtoDUNE) in 2 cryostats 1:20 scale croystats
  - single phase
  - new vertical drift concept

New:

- 2 large cryostats as European contribution to the LBNF/DUNE infrastructure

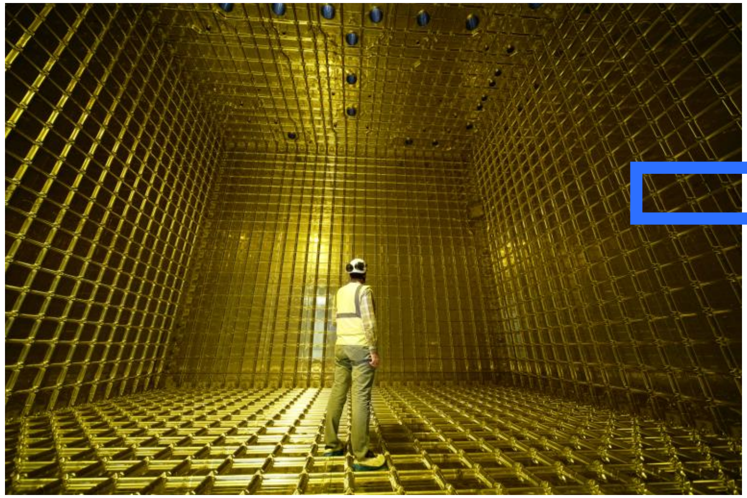
The Long-Baseline Neutrino Facility (LBNF) supporting the international Deep Underground Neutrino Experiment (DUNE)



“The LBNF/DUNE project will be the first internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy in the United States” - DOE

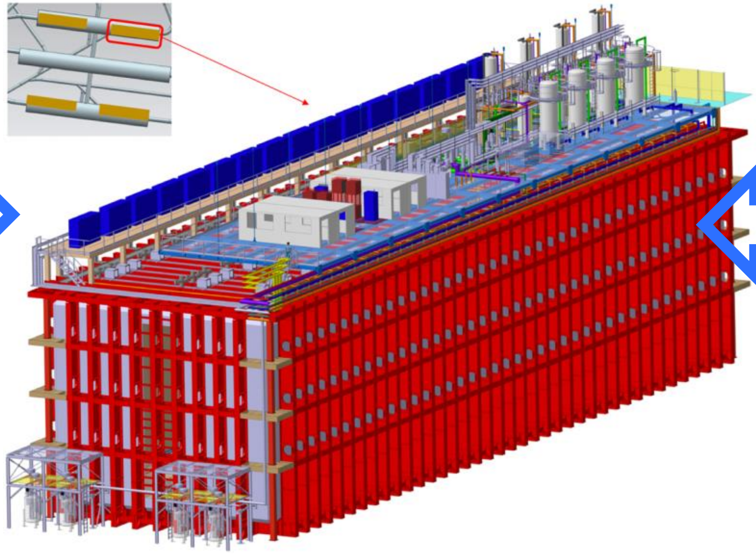
LBNF/DUNE Cryostats

CERN Neutrino Platform



2 cryostats NP02 and NP04
each ≈ 12×12×12 m^3

LBNF/DUNE cryostats



each of the 2 cryostats
≈ 66×18×19 m^3

Typical LNG ship

typically 155 000 m^3

→ challenge is the interpolation in size of the technology