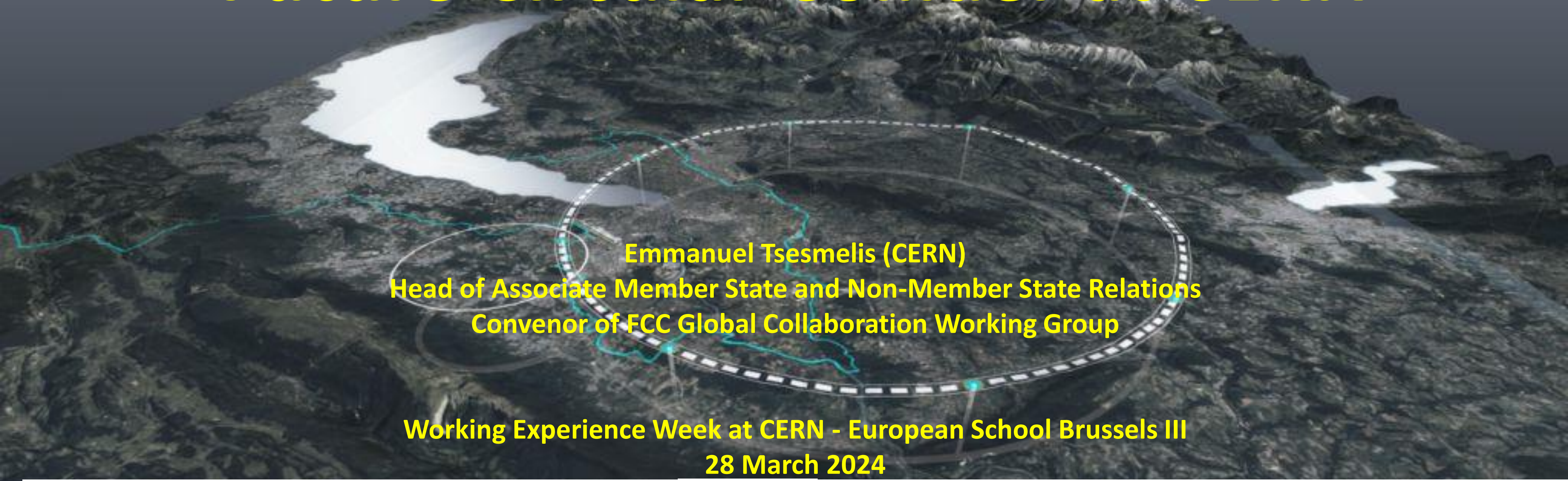
The Path Towards the Future Circular Collider at CERN



Emmanuel Tsesmelis (CERN)
Head of Associate Member State and Non-Member State Relations
Convenor of FCC Global Collaboration Working Group

Working Experience Week at CERN - European School Brussels III
28 March 2024

FUTURE CIRCULAR COLLIDER
Innovation Study

EuroCirCol
A key to New Physics

EASITrain

iFAST

E-JADE

EAJADE

CHART
Swiss Accelerator
Research and
Technology

http://cern.ch/fcc

CERN

*Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **EASITrain,** grant agreement no. 764879; **iFAST**, grant agreement 101004730, **FCCIS**, grant agreement 951754; **E-JADE,** contract no. 645479; **EAJADE**, contract number 101086276; and by the Swiss **CHART** program*

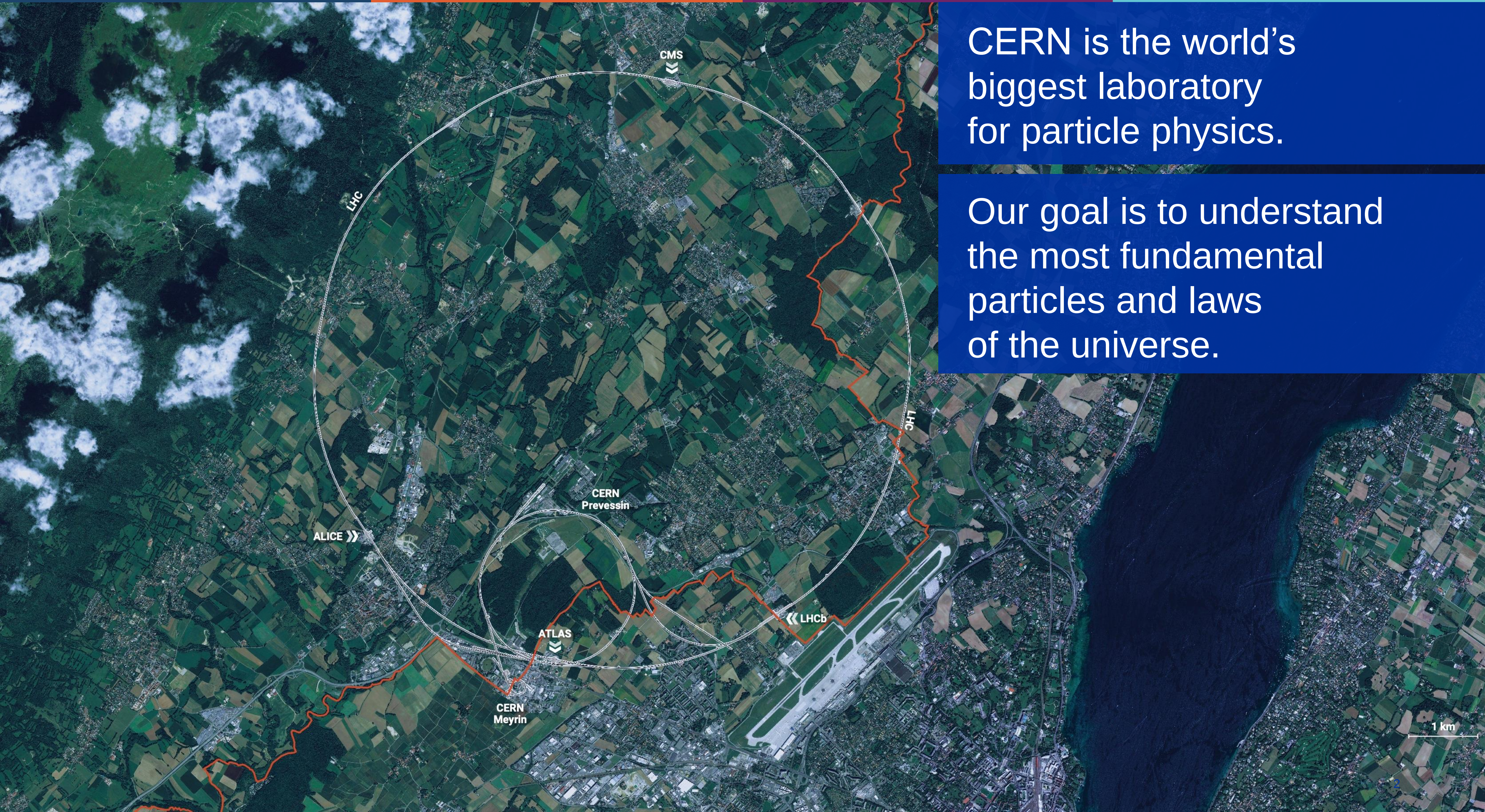
European
Commission

Horizon 2020
European Union funding
for Research & Innovation

photo: J. Wenninger

CERN is the world’s
biggest laboratory
for particle physics.

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



Four pillars underpin CERN’s mission

RESEARCH

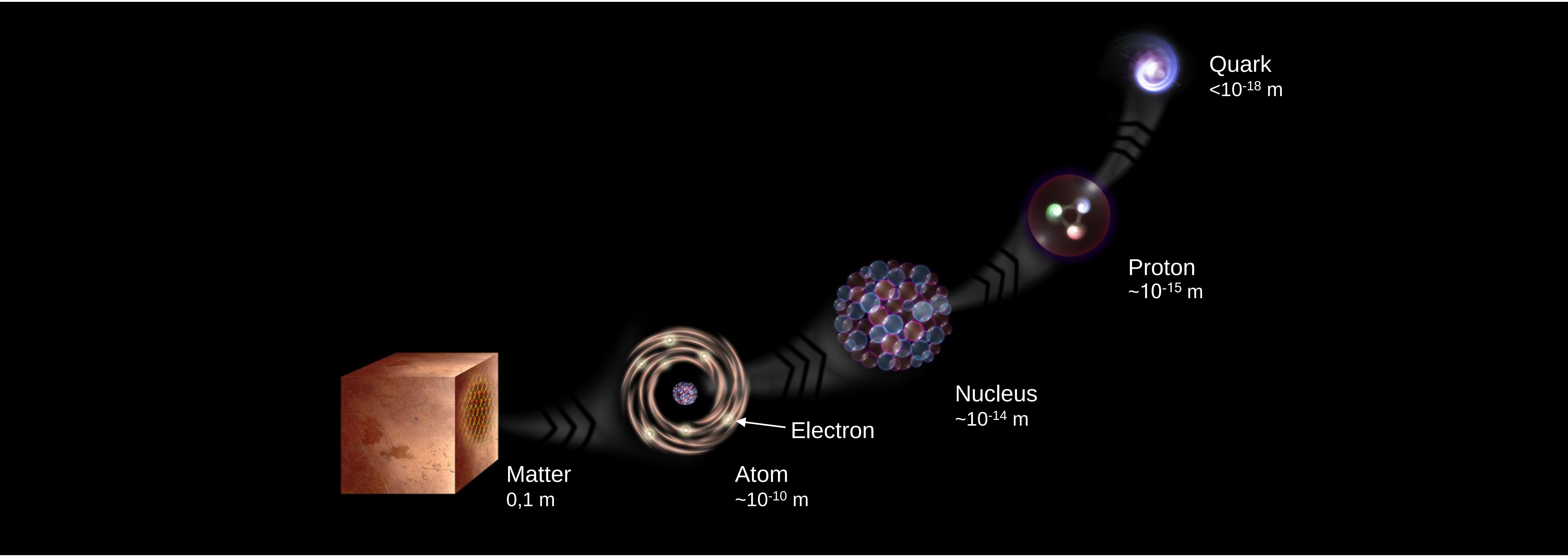
EDUCATION
& TRAINING

COLLABORATION

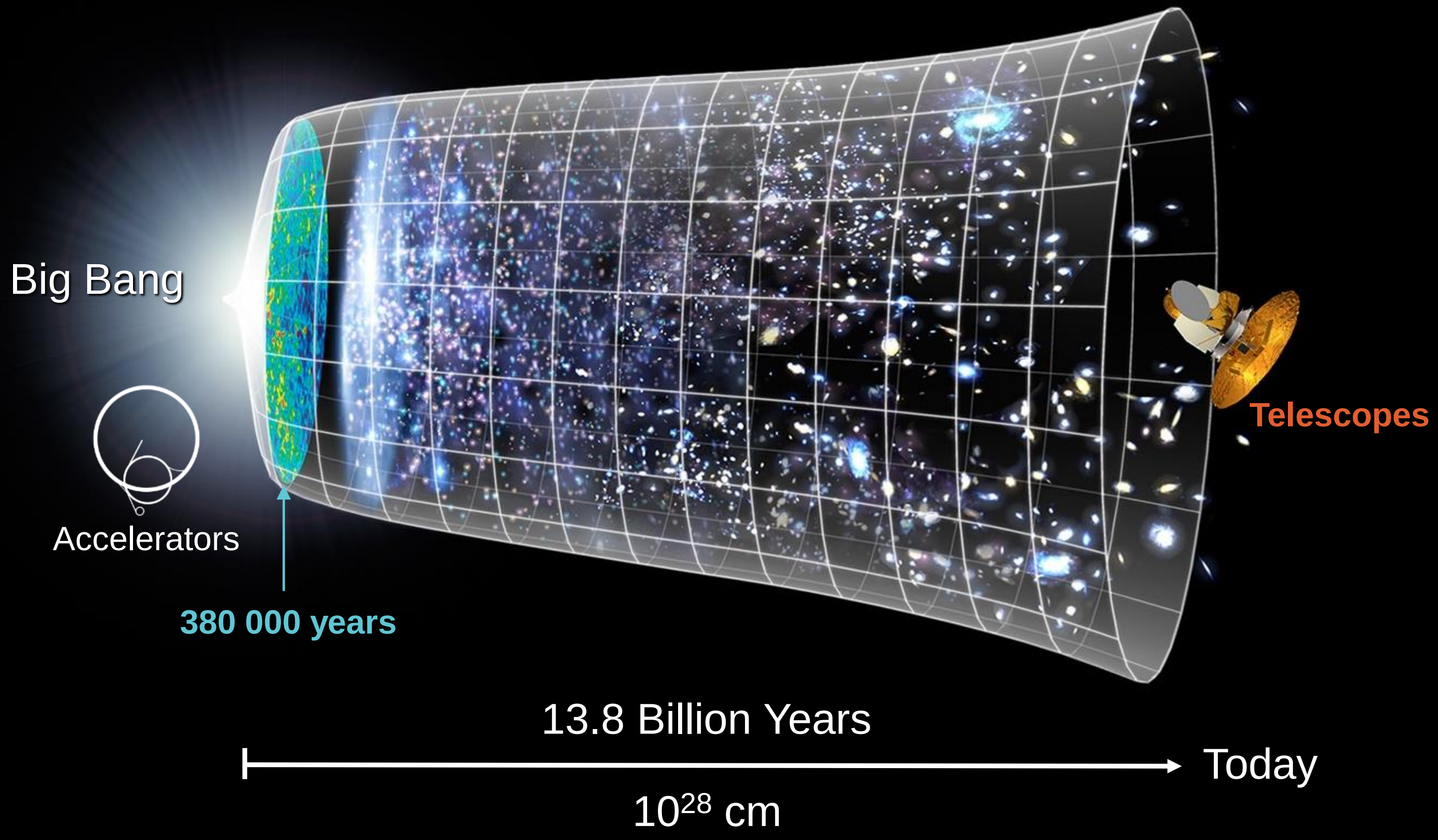
TECHNOLOGY
& INNOVATION

What is the universe made of?

We study the elementary building blocks of matter
and the forces that control their behaviour



How did the universe begin?



We reproduce the conditions a fraction of a second after the Big Bang, to gain insight into the structure and evolution of the universe.

Synergies with fields of astronomy, astrophysics and cosmology

At CERN we help to answer these questions


Carlo Rubbia

Simon Van der Meer

Georges Charpak

Several CERN scientists have received Nobel Prizes for key discoveries in particle physics.

The Higgs boson was discovered in 2012; without it fundamental particles would be massless and atoms could not form.


François Englert and Peter Higgs. With Robert Brout, they proposed the mechanism in 1964.

There are many unanswered questions in fundamental physics

Including

What is the unknown 95% of the mass and energy of the universe?

Is there only one Higgs boson, and does it behave exactly as expected?

Why is the universe made only of matter, with hardly any antimatter?

Why is gravity so weak compared to the other forces?

Accelerator Development

Characterised by rapid progress for over a century.

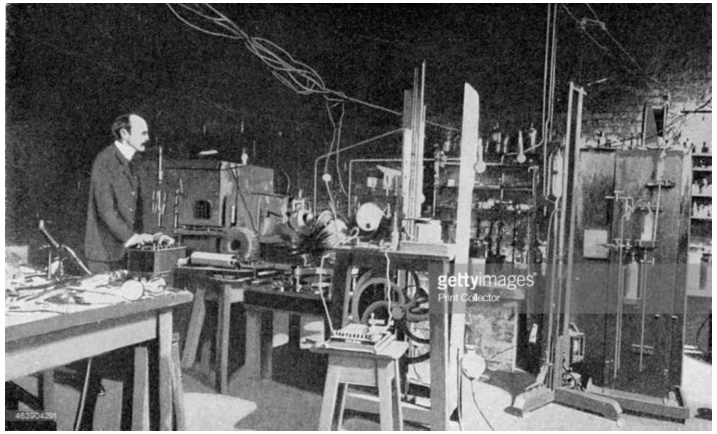
- From cathode-ray tubes to the LHC.
- From the discovery of the electron to the discovery of the Higgs boson.

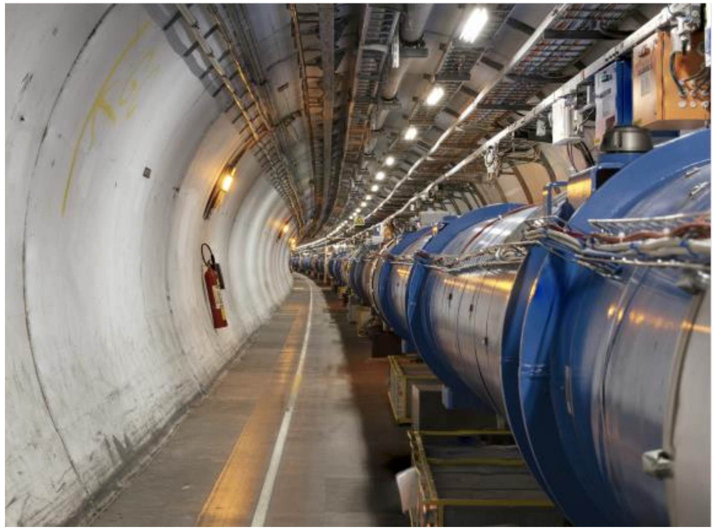
Advances in accelerators require corresponding advances in accelerator technologies

- Magnets, vacuum systems, RF systems, diagnostics,...

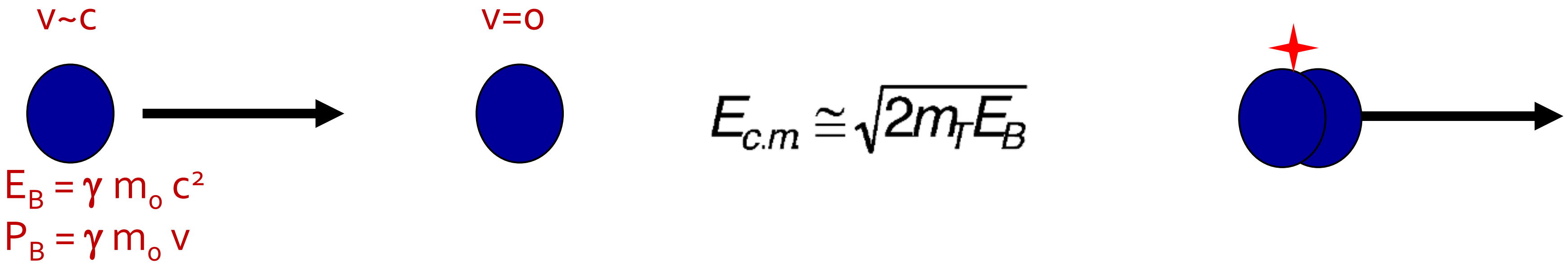
Timelines becoming long, requiring:

- Long-term planning.
- Long-term resources.
- Global collaboration.





Why Colliders?



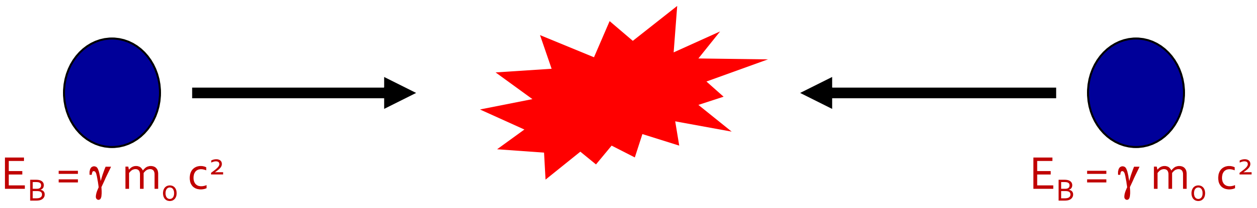
$E_B = \gamma m_0 c^2$

$P_B = \gamma m_0 v$

$$E_{c.m} \cong \sqrt{2 m_T E_B}$$

Only a tiny fraction of energy converted into mass of new particles
(due to energy and momentum conservation)

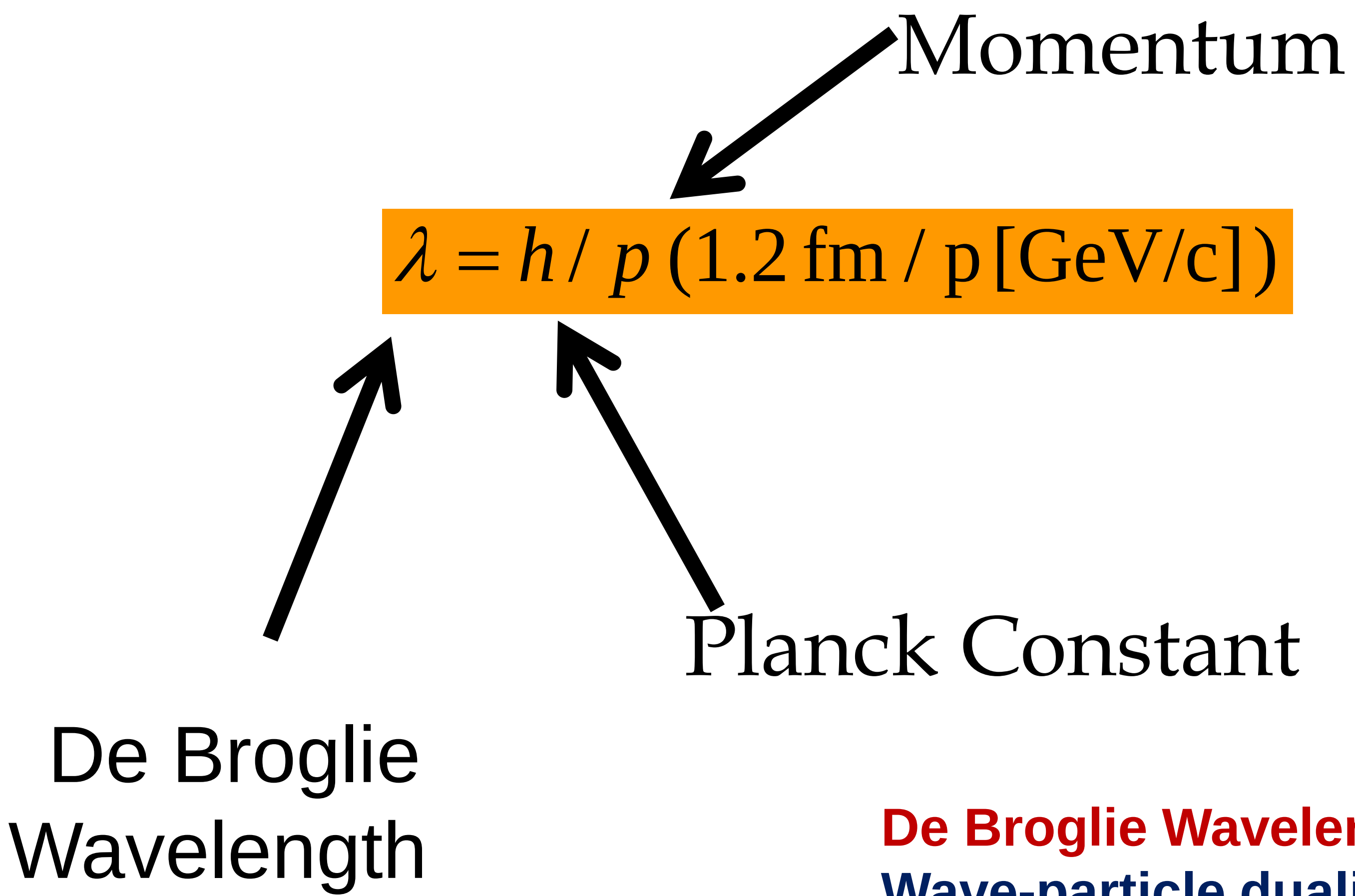
$$E_{c.m.} \cong 2\ E_B$$



$E_B = \gamma m_0 c^2$

$E_B = \gamma m_0 c^2$

De Broglie Wavelength



$$\lambda = h / p \; (1.2\,\text{fm} / \text{p}\,[\text{GeV/c}])$$

De Broglie Wavelength
Wave-particle duality;
For higher E, probe shorter distances inside matter

Luminosity

Particle colliders designed to deliver two basic parameters to HEP user.

- Measure of collision rate per unit area.
- Event rate for given event probability (“cross-section”):

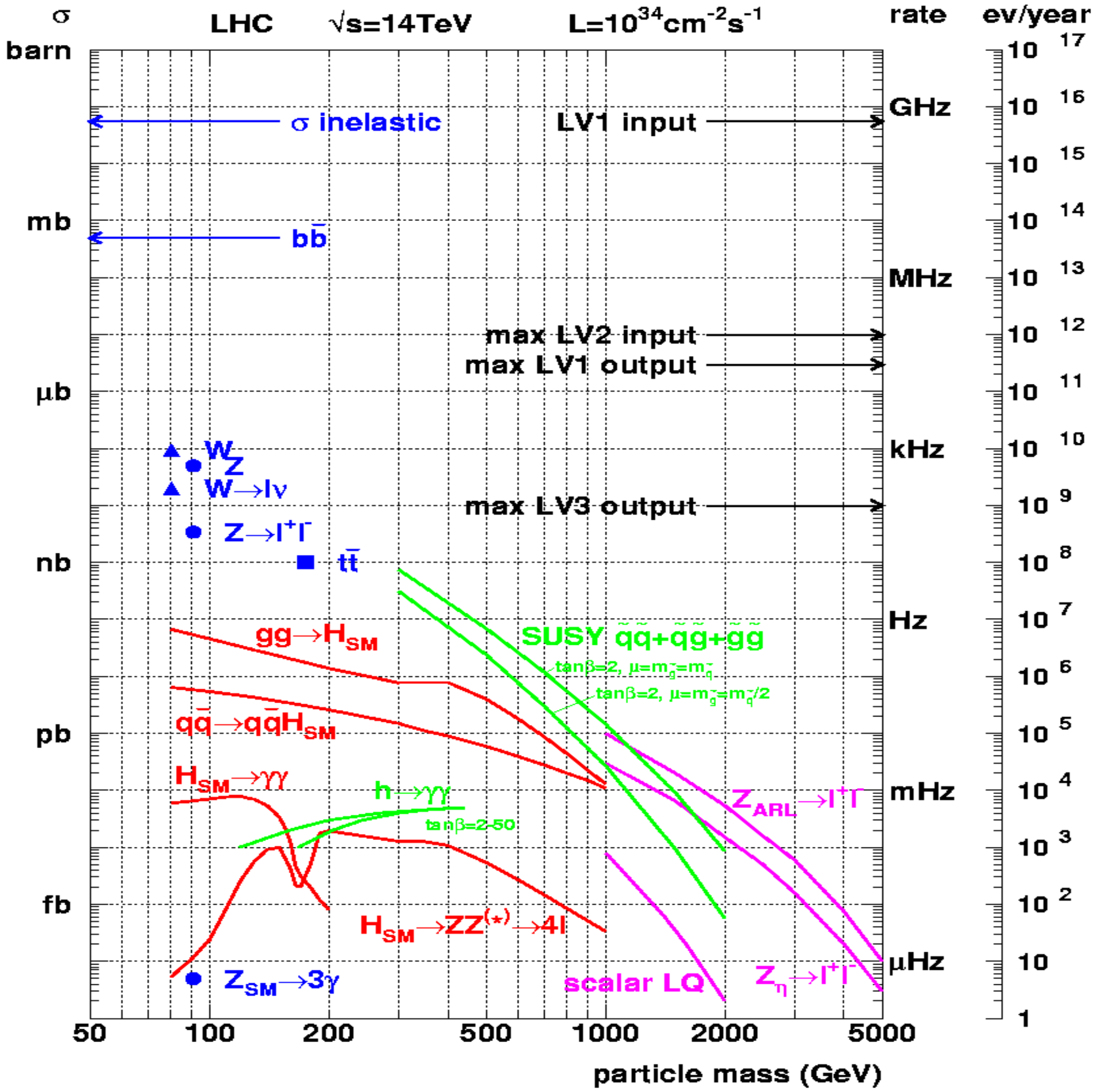
For a Collider, instantaneous luminosity L is given by

$$\boxed{R = \mathcal{L}\,\sigma}$$

- → Require intense beams, high bunch frequency and small beam sizes at IP.

$$\boxed{\frac{N_+ N_- f_c}{4\pi \sigma_x^* \sigma_y^*}}$$

Cross-sections at the LHC



“Well known” processes. Don’ t need to keep all of them …

New Physics!!

We want to keep!!

Collider Types

- Hadron Colliders
  - Desire high energy
    - Only ~10% of beam energy available for hard collisions producing new particles
      - Need *O*(10 TeV) Collider to probe 1 TeV mass scale.
      - High-energy beam requires strong magnets to store and focus beam in reasonable-sized ring.
  - Desire high luminosity
    - Use proton-proton collisions.
      - High bunch population and high bunch frequency.
    - Anti-protons difficult to produce if beam is lost
      - *c.f.* SPS Collider and Tevatron

Collider Types

- Lepton Colliders (e+e-)
  - Synchrotron radiation is the most serious challenge
    - Energy loss of a particle per turn

$$u=\underbrace{\frac{4\pi}{3}\frac{r}{\left(m_0c^2\right)^3}}_{C}E^4\int\frac{1}{\rho^2}d\rho\quad=-\frac{CE^4}{\rho}$$

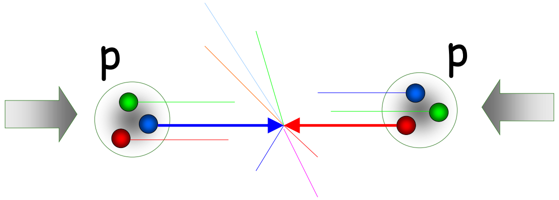
    - Emitted power in circular machine is

$$P_{SR}[\mathrm{kW}]=\frac{88.5\,E^4[\mathrm{GeV}]I[\mathrm{A}]}{\rho[\mathrm{m}]}$$

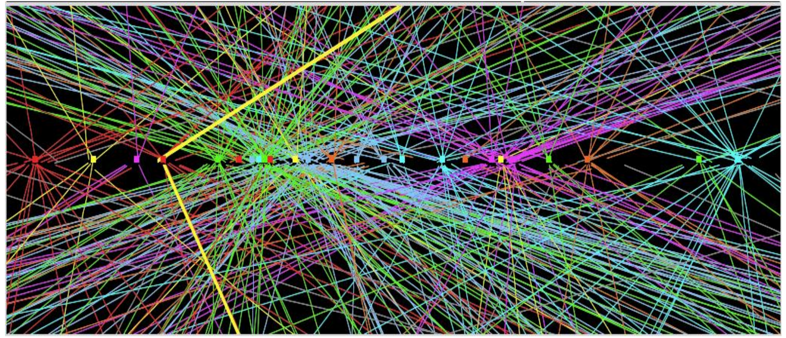
    - For collider with E_{CM} = 1 TeV in the LHC tunnel with a 1 mA beam, radiated power would be 2 GW
      - Would need to replenish radiated power with RF
      - Remove it from vacuum chamber
  - Approach for high energies is Linear Collider.

Collider Characteristics

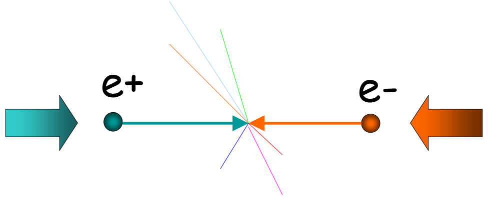
- Hadron collider at the frontier of physics
  - Huge QCD background
  - Not all nucleon energy available in collision

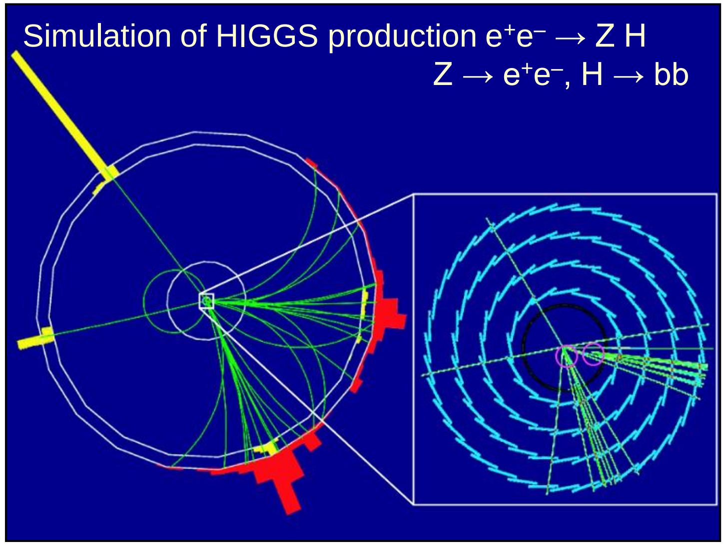


ATLAS Z → μμ event from 2012 data with 25 reconstructed vertices



- Lepton collider for precision physics
  - Well defined initial energy for reaction
  - Colliding point like particles





Simulation of HIGGS production $e^+e^- \rightarrow Z\,H$

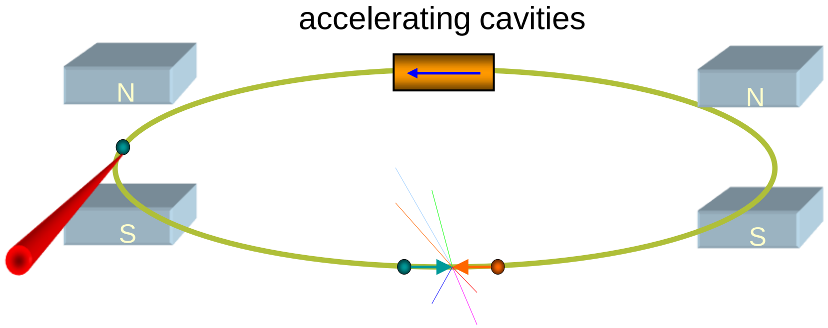
$Z \rightarrow e^+e^-$, $H \rightarrow bb$

The Higgs is hiding in thousands of trillions interactions…

Z→ μμ event from 2012 data with 25 reconstructed vertices

Z→ μμ

Circular versus Linear Collider

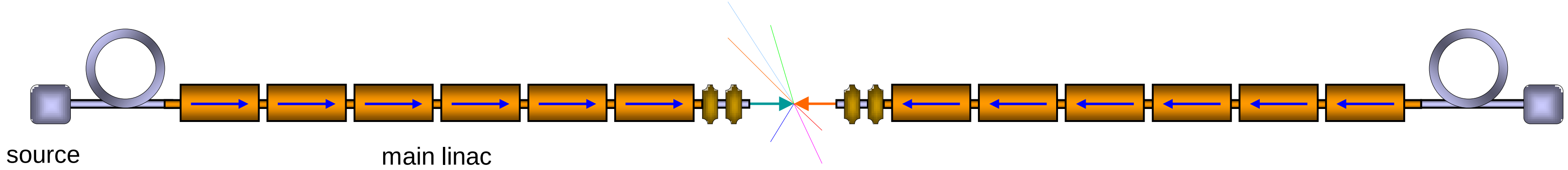


Circular Collider

many magnets, few cavities, stored beam

higher energy → stronger magnetic field

→ higher synchrotron radiation losses (E^4/m^4R)

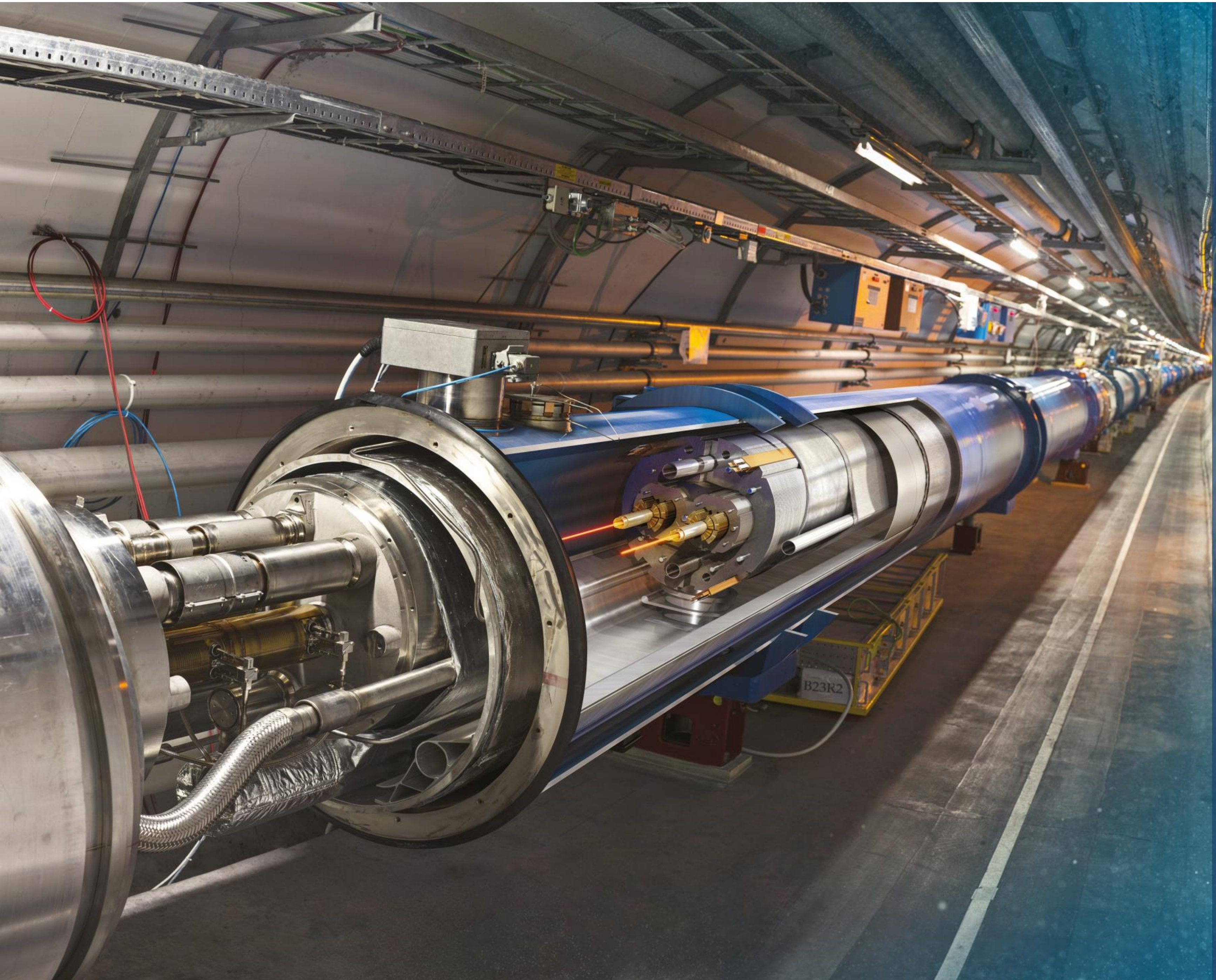


Linear Collider

few magnets, many cavities, single pass beam

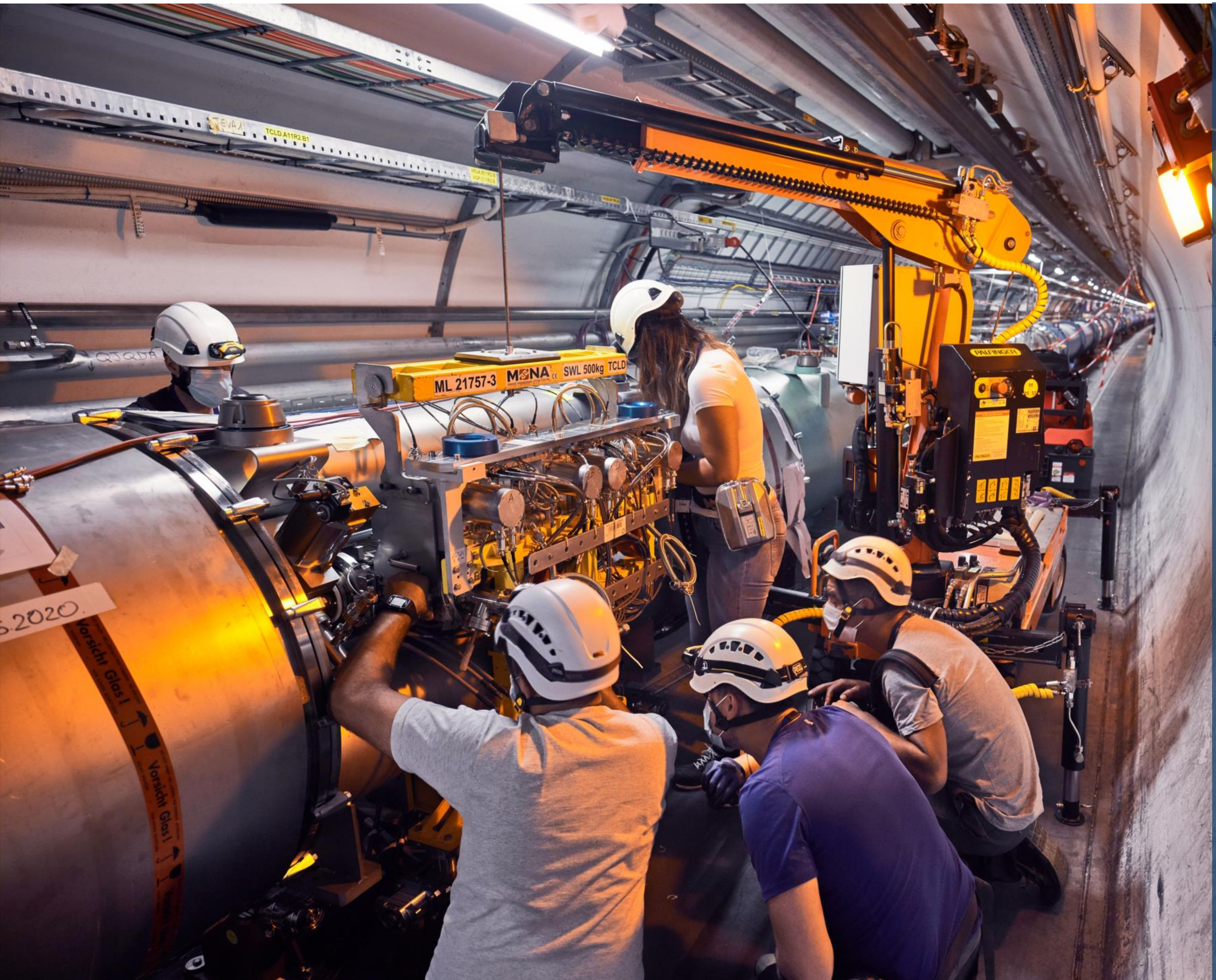
higher energy → higher accelerating gradient

higher luminosity → higher beam power (high bunch repetition)



Large Hadron Collider (LHC)

- 27 km in circumference
- About 100 m underground
- Superconductivity is the enabling technology for magnets and RF cavities.



Upgrade to the High-Luminosity LHC is under way

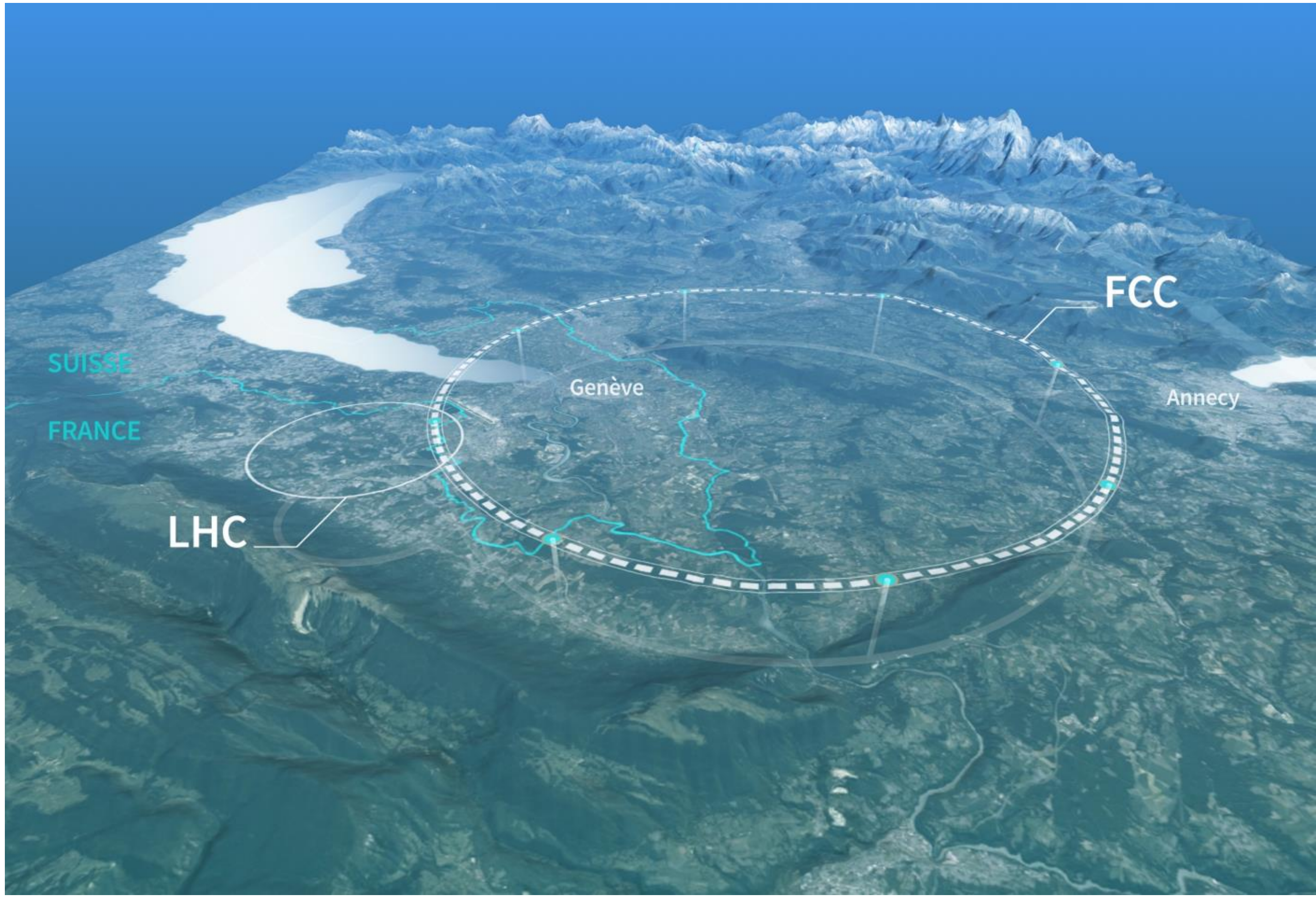
- The HL-LHC will use new technologies to provide 10 times more collisions than the LHC.
- It will give access to rare phenomena, improved precision and discovery potential.
- It will start operating in 2029 and run until 2040.

The LHC / HL-LHC will make significant progress but new collider needed to advance research in totally new areas.

Preparing CERN’s Future

Driven by the **2020 Update of the European Strategy for Particle Physics**

- Technical and financial feasibility study of a Future Circular Collider (**FCC**).
- Accelerator R&D to develop technologies for FCC and for alternative options.
- Detector and computing R&D.
- Maintain and expand a compelling scientific diversity programme.
- Continue to support other projects around the world.



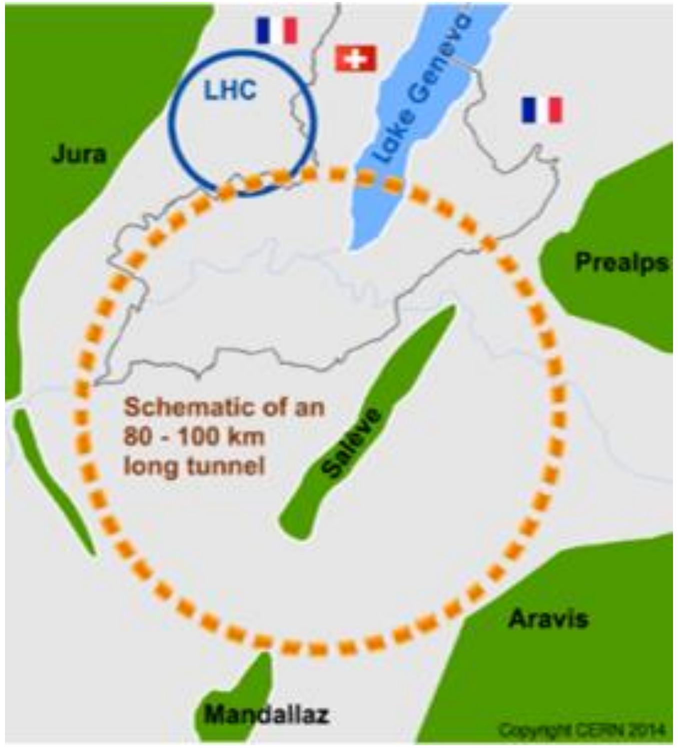
CERN Research Infrastructure

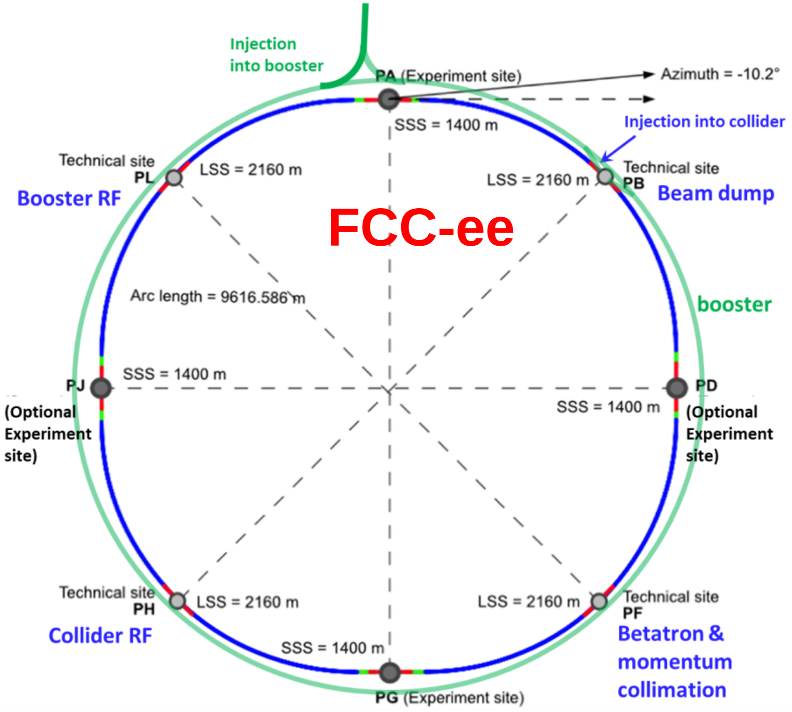
photo: J. Wenninger

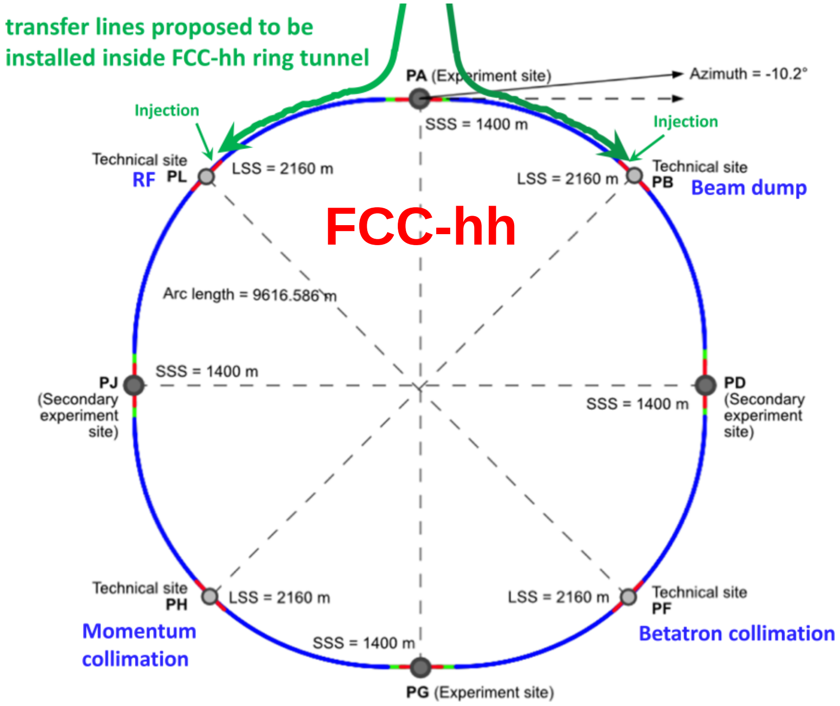
FCC Integrated Programme

Comprehensive long-term programme maximising physics opportunities

- **Stage 1: FCC-ee (Z, W, H, tt̅) as Higgs factory, electroweak & top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- Highly synergetic and complementary programme boosting the physics reach of both colliders
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC







The LHC Legacy (so far)

- **Standard Model (SM) confirmed to high accuracy up to energies of several TeV**
  (thanks to a firm control of exp. & th. syst. uncertainties, the LHC became a precision machine)
- **Higgs boson discovered** at the mass predicted* by LEP precision EW measurements

  *within the Standard Model
- **Absence of new physics**
  - TeV-scale Naturalness might not explain DM/baryogenesis
  - Traditional New Physics models are under siege
  - New approaches: relaxion, Nnaturalness, clockwork…
  - Cosmology might settle the vacuum of the SM

We need a **broad**, **versatile** and **ambitious** programme that
1. **Sharpens** our knowledge of already discovered physics
2. **Pushes** the frontiers of the unknown at high and low scales

Together FCC-ee & FCC-hh combine these two aspects

More PRECISION <u>and</u> more ENERGY for more SENSITIVITY to New Physics

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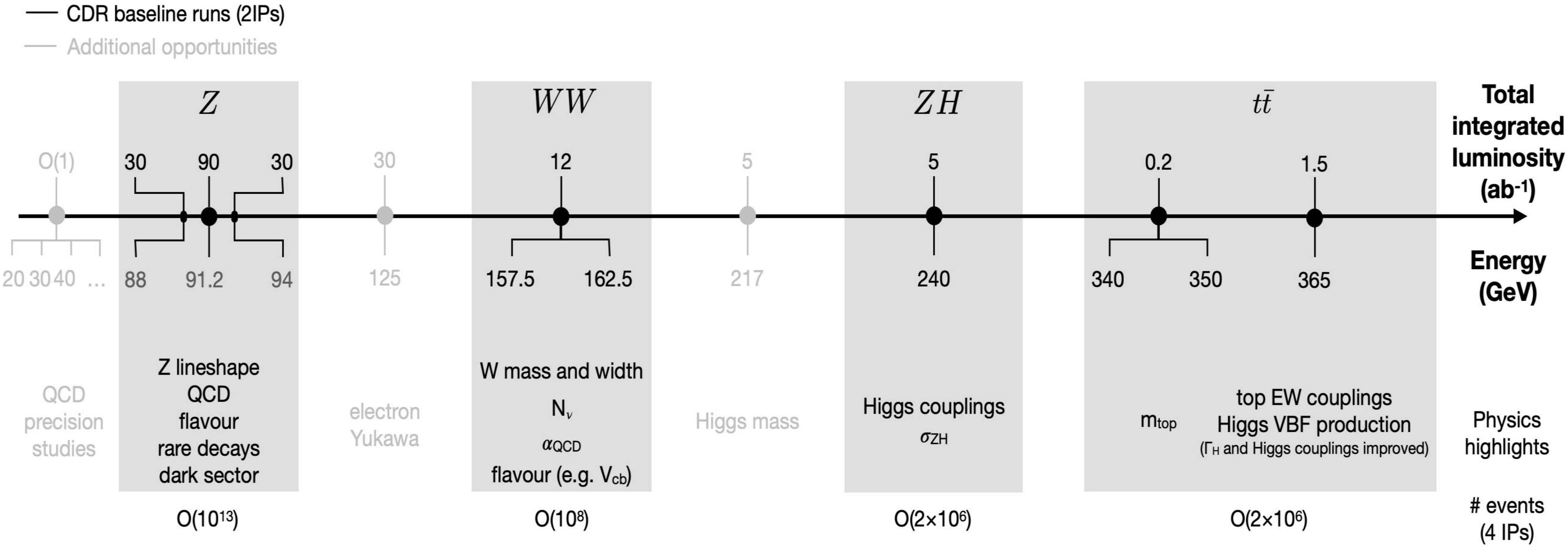
FCC-ee Collider Programme



- **Opportunities** beyond the baseline plan (√s below Z, 125GeV, 217GeV; larger integrated lumi…)
- **Opportunities** to exploit FCC facility differently (to be studied more carefully):
  - using the electrons from the injectors for beam-dump experiments,
  - extracting electron beams from the booster,
  - reusing the synchrotron radiation photons.

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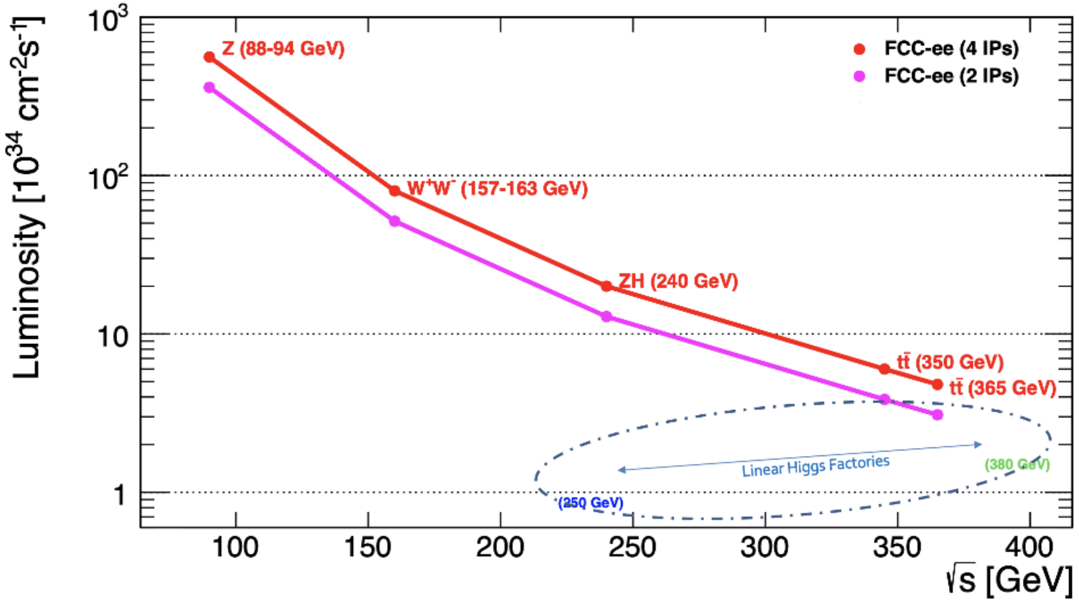
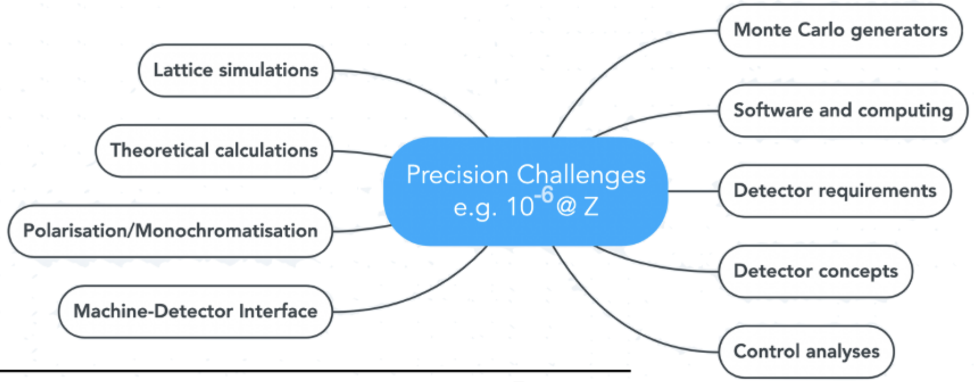
FCC-ee Run Plan

LEP1 data accumulated in **every 2 mn**. Exciting & diverse programme with different priorities every few years.
(order of the different stages still subject to discussion/optimisation)



Statistics achieved in

in each detector:
10^5 Z/sec, 10^4 W/hour,
1500 Higgs/day, 1500 top/day


Precision Challenges
e.g. 10^{-6} @ Z

Lattice simulations
Theoretical calculations
Polarisation/Monochromatisation
Machine-Detector Interface
Monte Carlo generators
Software and computing
Detector requirements
Detector concepts
Control analyses

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^8 WW		1.45×10^6 ZH + 45k WW → H	1.9×10^6 $t\bar{t}$ +330k ZH +80k WW → H	

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FCC-ee Explore and Discover

EXPLORE INDIRECTLY the 10 -100 TeV energy scale with precision measurements
From the correlated properties of the Z , b, c, τ, W, Higgs, and top particles
Up to 20-50-fold improved precision on ALL electroweak observables (EWPO)
→ m_Z , m_W , m_{top} , Γ_Z , $\sin^2 \theta_W^{eff}$, R_b , $\alpha_{QED}(m_Z)$, $\alpha_s(m_Z\ m_W\ m_t)$, top EW couplings …
Up to 10 × more precise and model-independent Higgs couplings (width, mass) measurements
→ Access the Higgs potential and infer the vacuum structure of the Universe
→ Reveals the dynamics of the EW phase transition and infer the fate of the EW vacuum

DISCOVER that the Standard Model does not fit
New Physics! → Pattern of deviations may point to the source.

DISCOVER a violation of flavour conservation / universality
$Z\to\tau\mu$ in 5x10^{12} Z decays; $\tau\to\mu\nu/e\nu$ in 2×10^{11} τ decays; $B^0\to K^{*0}\tau^+\tau^-$ or $B_S\to\tau^+\tau^-$ in 10^{12} bb evts

DISCOVER dark matter, e.g., as invisible decays of Higgs or Z

DISCOVER DIRECTLY elusive (aka feebly-coupled) particles
in the 5-100 GeV mass range, such as right-handed neutrinos, dark photons, light Higgs-like scalars, dilaton, ALPs, relaxions…

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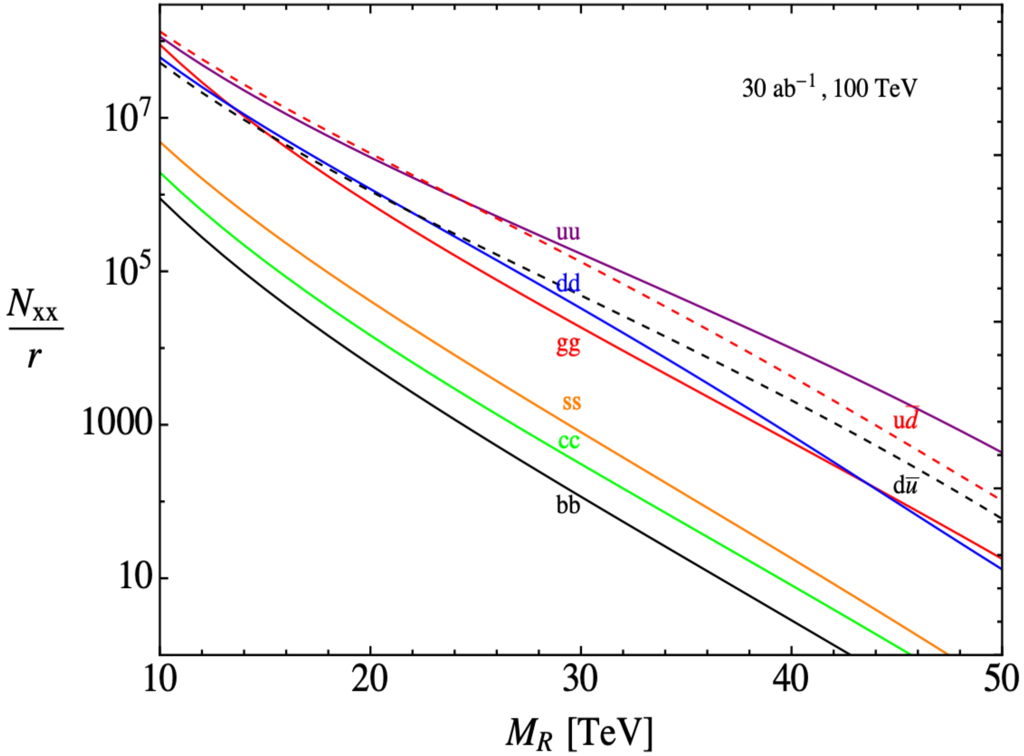
FUTURE
CIRCULAR
COLLIDER

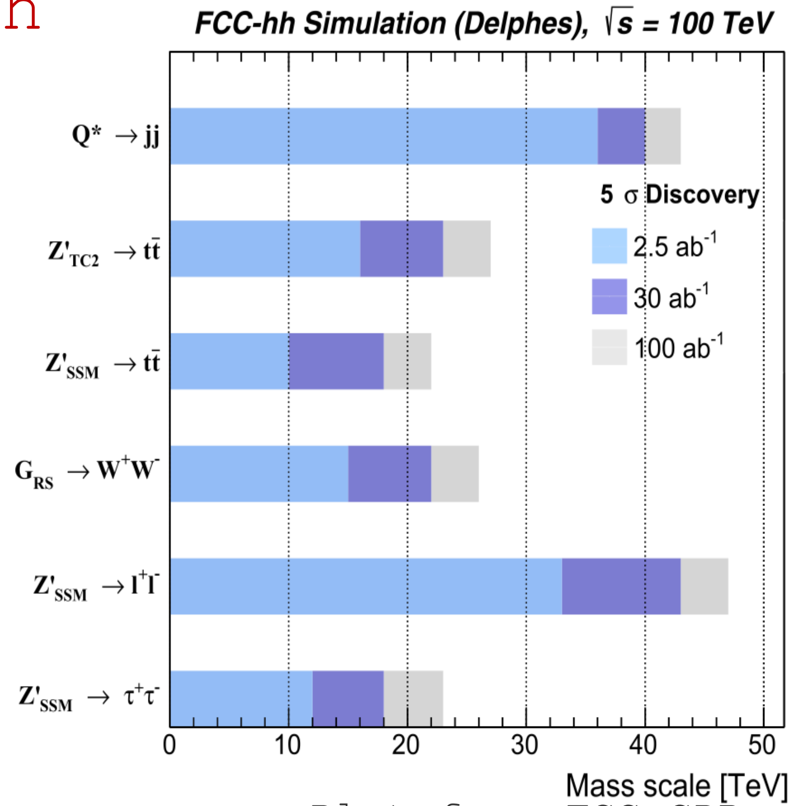
FCC-hh Particle Resonance Production

Number of Resonances Produced



Plot from mid-term report

FCC-hh Mass Reach



Plot from FCC CDR

FCC-hh effectively collides 196 different initial states, perfect exploratory machine

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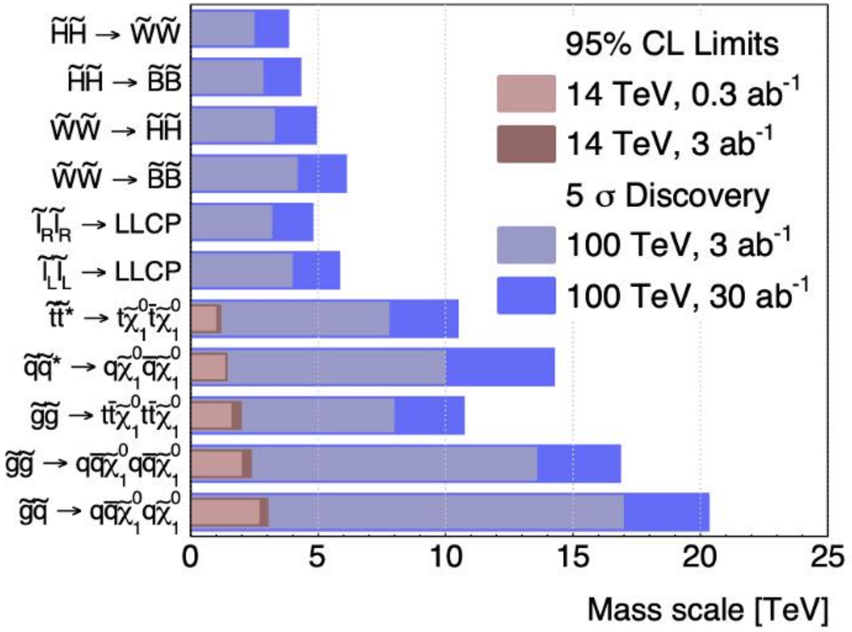
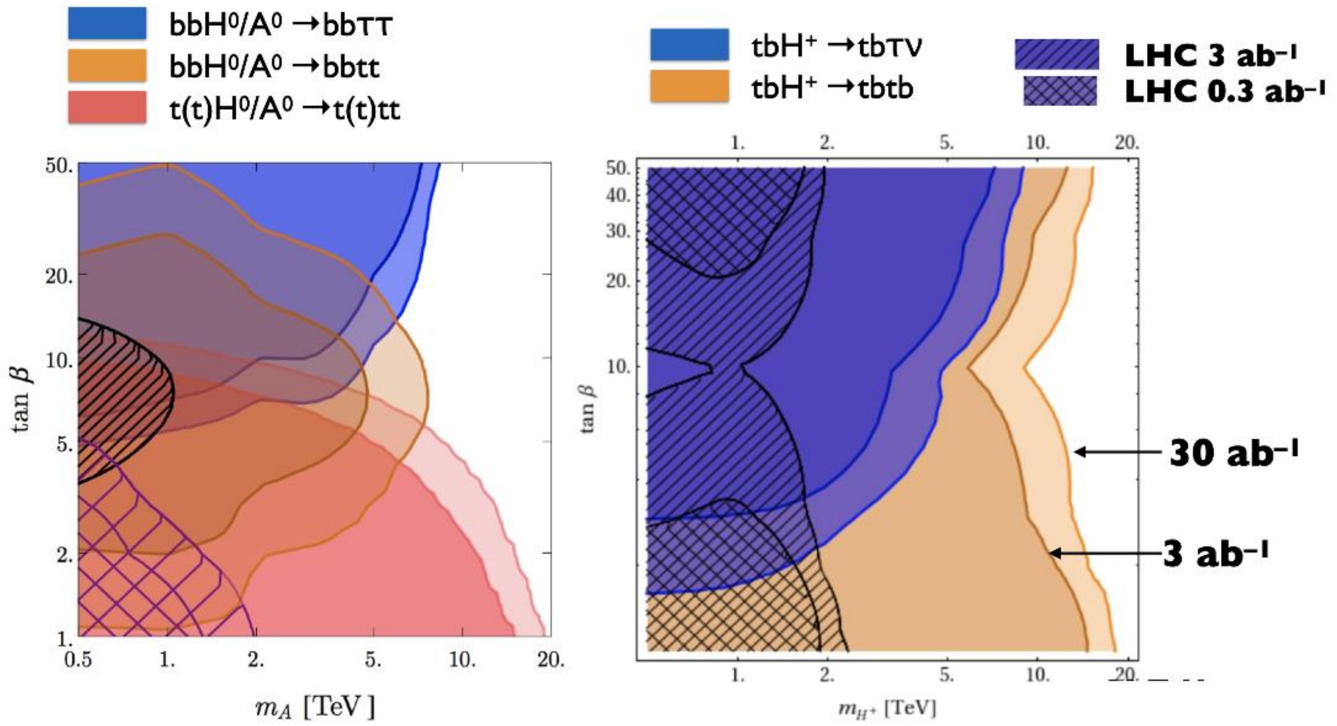
FCC-hh Beyond the Standard Model - SUSY



Plot from arXiv:1606.00947



Plot from arXiv:1605.08744 and arXiv:1504.07617

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FUTURE CIRCULAR COLLIDER

European Strategy for Particle Physics – The Roadmap

2013 Update of European Strategy for Particle Physics:

"CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines."

→ FCC Conceptual Design Reports (2018/19)

The European Physical Journal
Offprint
EPJ C
Particles and Fields
FCC Physics Opportunities
Future Circular Collider Conceptual Design Report Volume 1
Michelangelo Mangano et al. (Eds.)
Springer

The European Physical Journal
EPJ ST
Special Topics
FCC-ee: The Lepton Collider
Future Circular Collider Conceptual Design Report Volume 2
Michael Benedikt et al. (Eds.)
edp sciences Springer

The European Physical Journal
EPJ ST
Special Topics
FCC-hh: The Hadron Collider
Future Circular Collider Conceptual Design Report Volume 3
Michael Benedikt et al. (Eds.)
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The European Physical Journal
EPJ ST
Special Topics
HE-LHC: The High Energy Large Hadron Collider
Future Circular Collider Conceptual Design Report Volume 4
Frank Zimmermann et al. (Eds.)
edp sciences Springer

Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC

CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 , EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

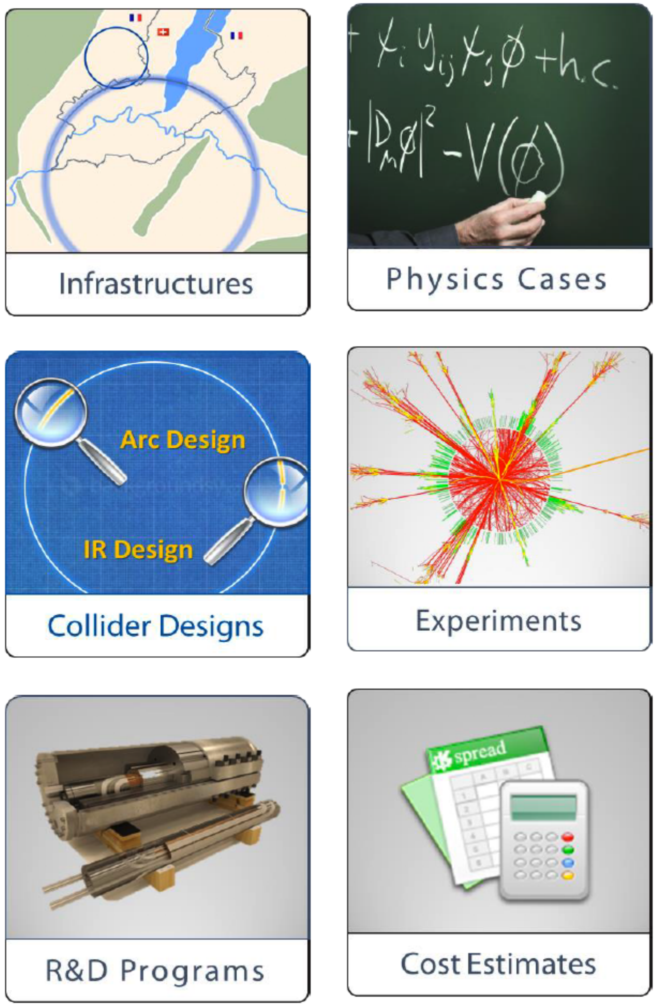
2020 Update of European Strategy for Particle Physics:

"Europe, together with its international partners, should investigate 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."

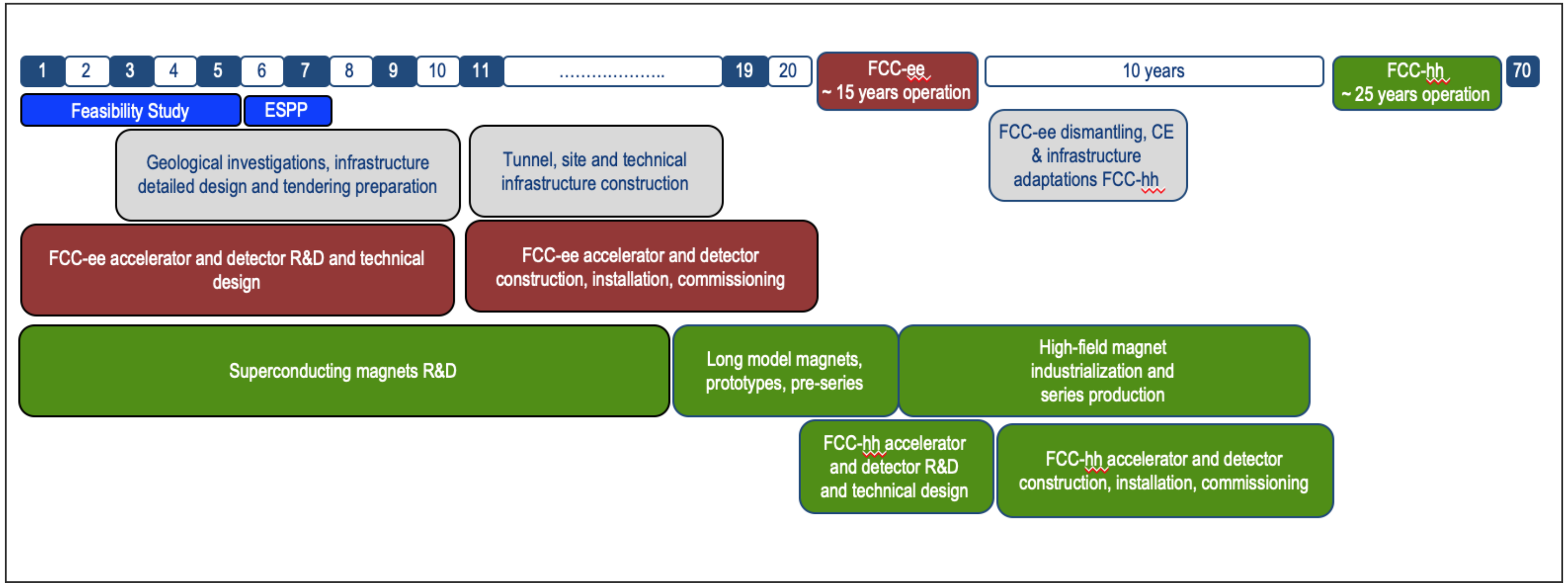
High-level Goals of Feasibility Study

High-level goals of Feasibility Study

- optimisation of placement and layout of the ring and related infrastructure, and demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas;
- pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval, with a focus on identifying and surmounting possible showstoppers;
- optimisation of the design of the colliders and their injector chains, supported by targeted R&D to develop the needed key technologies;
- development and documentation of the main components of the technical infrastructure;
- elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, environmental aspects and energy efficiency;
- identification of substantial resources from outside CERN’s budget for the implementation of the first stage of a possible future project;
- consolidation of the physics case and detector concepts for both colliders.

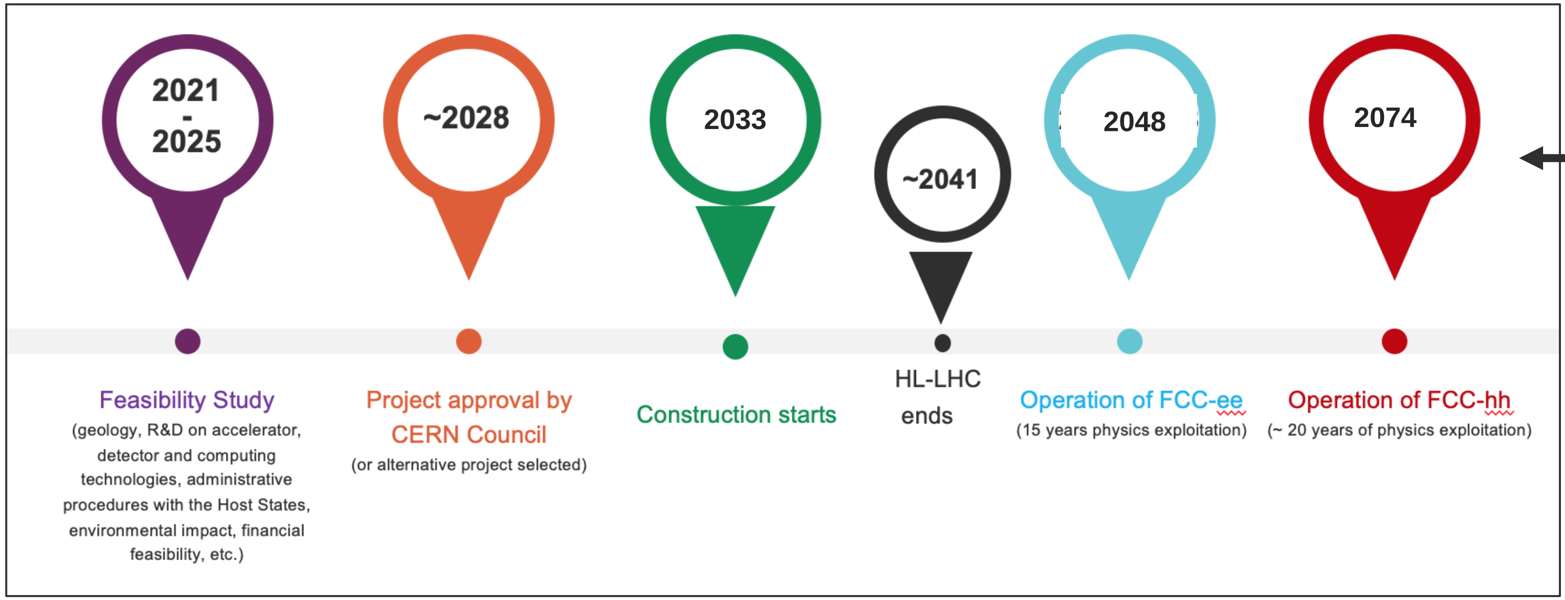


FCC Integrated Programme - Timeline



Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018

FCC construction can proceed in parallel with HL-LHC operation.



Feasibility Study
(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

Project approval by CERN Council
(or alternative project selected)

Construction starts

HL-LHC ends

Operation of FCC-ee
(15 years physics exploitation)

Operation of FCC-hh
(~ 20 years of physics exploitation)

"Realistic" schedule taking into account:
- ❑ past experience in building colliders at CERN
- ❑ approval timeline: ESPP, Council decision
- ❑ that HL-LHC will run until 2041

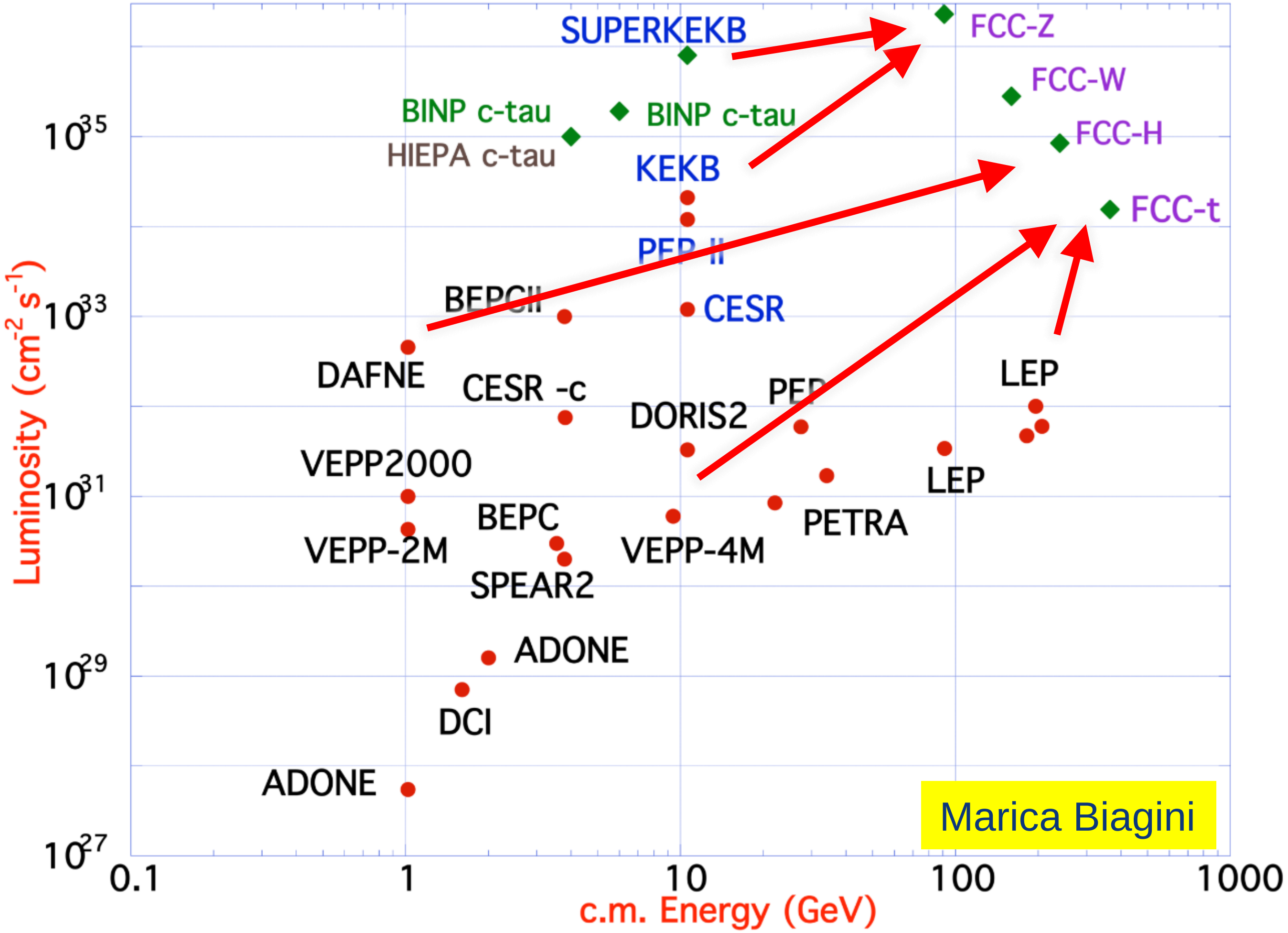
Can be accelerated if more resources available

FCC-ee in a Nutshell

- **High luminosity precision study of Z, W, H, and $t\bar{t}$**
  - 2×10^{36} cm^{-2}s^{-1}/IP at Z (or total ~10^{37} cm^{-2}s^{-1} with 4 IPs)
  - 7×10^{34} cm^{-2}s^{-1} at ZH, 1.3×10^{34} cm^{-2}s^{-1} at $t\bar{t}$
  - Unprecedented energy resolution at Z (<100 keV) and W (<300 keV)
- **Low-risk technical solution** based on 60 years of e^+e^- circular colliders and particle detectors ; R&D on components for improved performance, but no need for “demonstration” facilities; LEP2, VEPP-4M, PEP-II, KEKB, DAΦNE, or SuperKEKB already used many of the key ingredients in routine operation
- Infrastructure will support a **century of exciting physics of discovery**
  - FCC-ee → FCC-hh → FCC-eh and/or several other options (FCC-μμ, Gamma Factory ..)
- **Utility requirements** similar to CERN existing use
- **Strong support** from CERN, partners & particle physics roadmaps (Europe, US)
- **Detailed multi-domain feasibility study underway** for next European Strategy

FCC-ee Design Concept

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



Marica Biagini

B-factories: **KEKB & PEP-II:**
- double-ring lepton colliders,
- high beam currents,
- top-up injection

DAFNE: crab waist, double ring

S-KEKB: low β_y^*, 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-ee: Main Machine Parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

4 years
5 x 10^{12} Z
LEP x 10^5

2 years
> 10^8 WW
LEP x 10^4

3 years
2 x 10^6 H

5 years
2 x 10^6 tt pairs

Design and parameters dominated by the choice to allow for 50 MW synchrotron radiation per beam.

- Up to x2000 improvement on all EW observables
- Up to x10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

F. Gianotti

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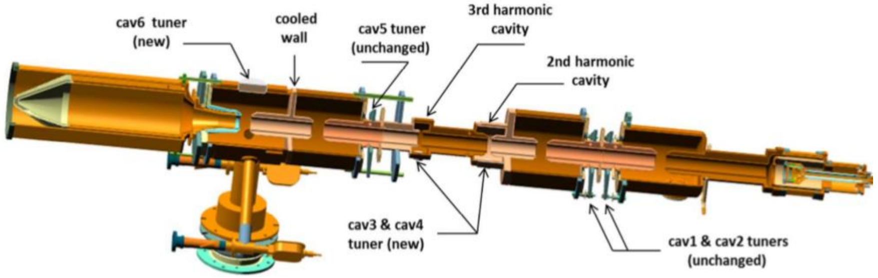
FCC-ee Accelerator R&D Examples

Efficient RF power sources
(400 & 800 MHz)

I. Syratchev

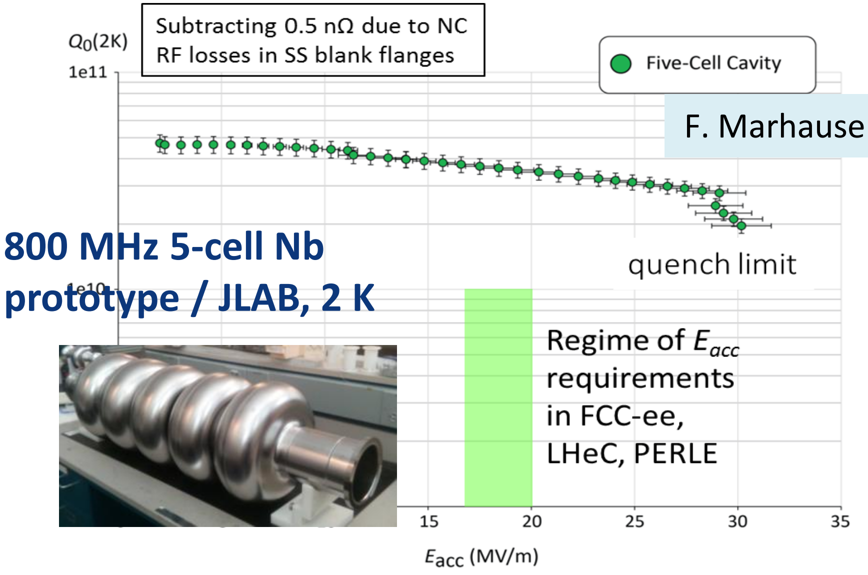


400 MHz 1-,2- & 4-cell Nb/Cu , 4.5 K

FPC & HOM coupler, cryomodule, thin-film coatings…

Efficient SC cavities

Jefferson Lab



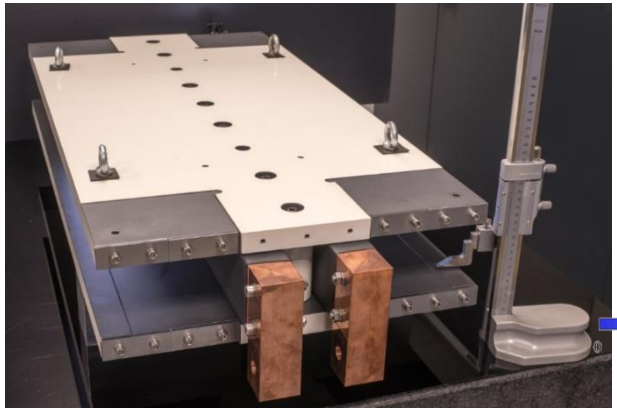
Subtracting 0.5 nΩ due to NC RF losses in SS blank flanges

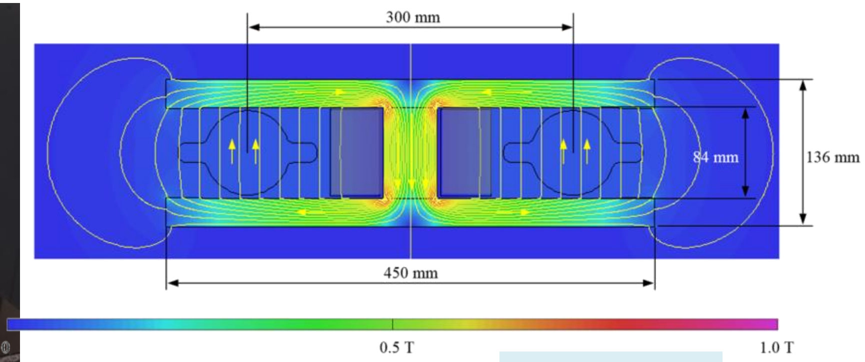
800 MHz 5-cell Nb prototype / JLAB, 2 K

Regime of E_{acc} requirements in FCC-ee, LHeC, PERLE

F. Marhauser

Energy **efficient** twin aperture **arc dipoles**

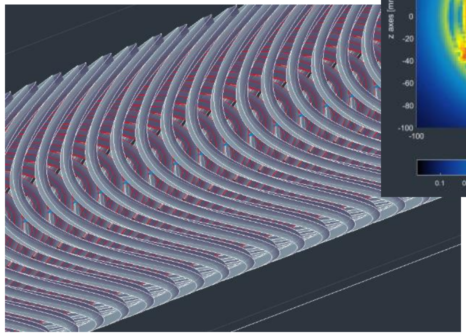


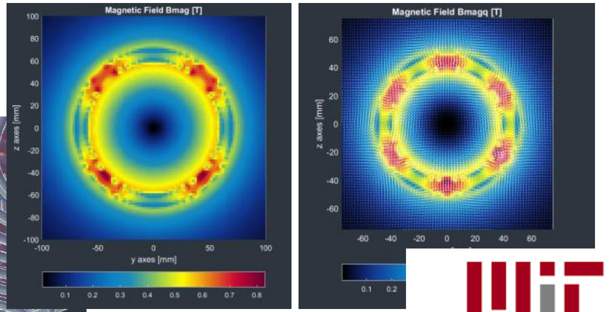


A. Milanese

Under study: **CCT HTS quad's & sext's for arcs**

PAUL SCHERRER INSTITUT
PSI





Massachusetts Institute of Technology

M. Koratzinos

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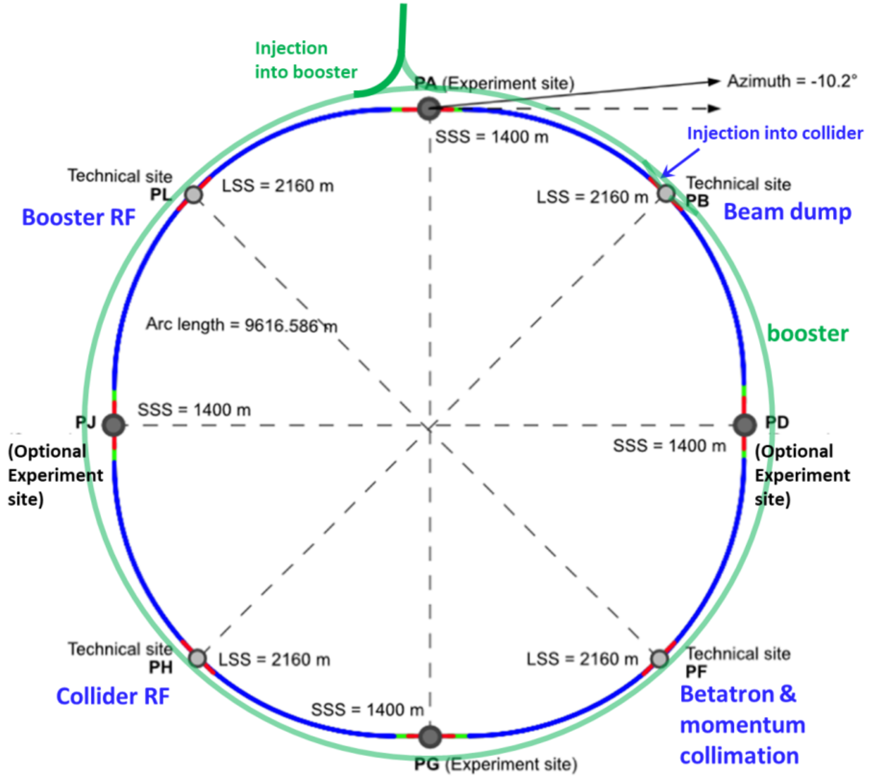
Optimised Placement and Lay-out for Feasibility Study

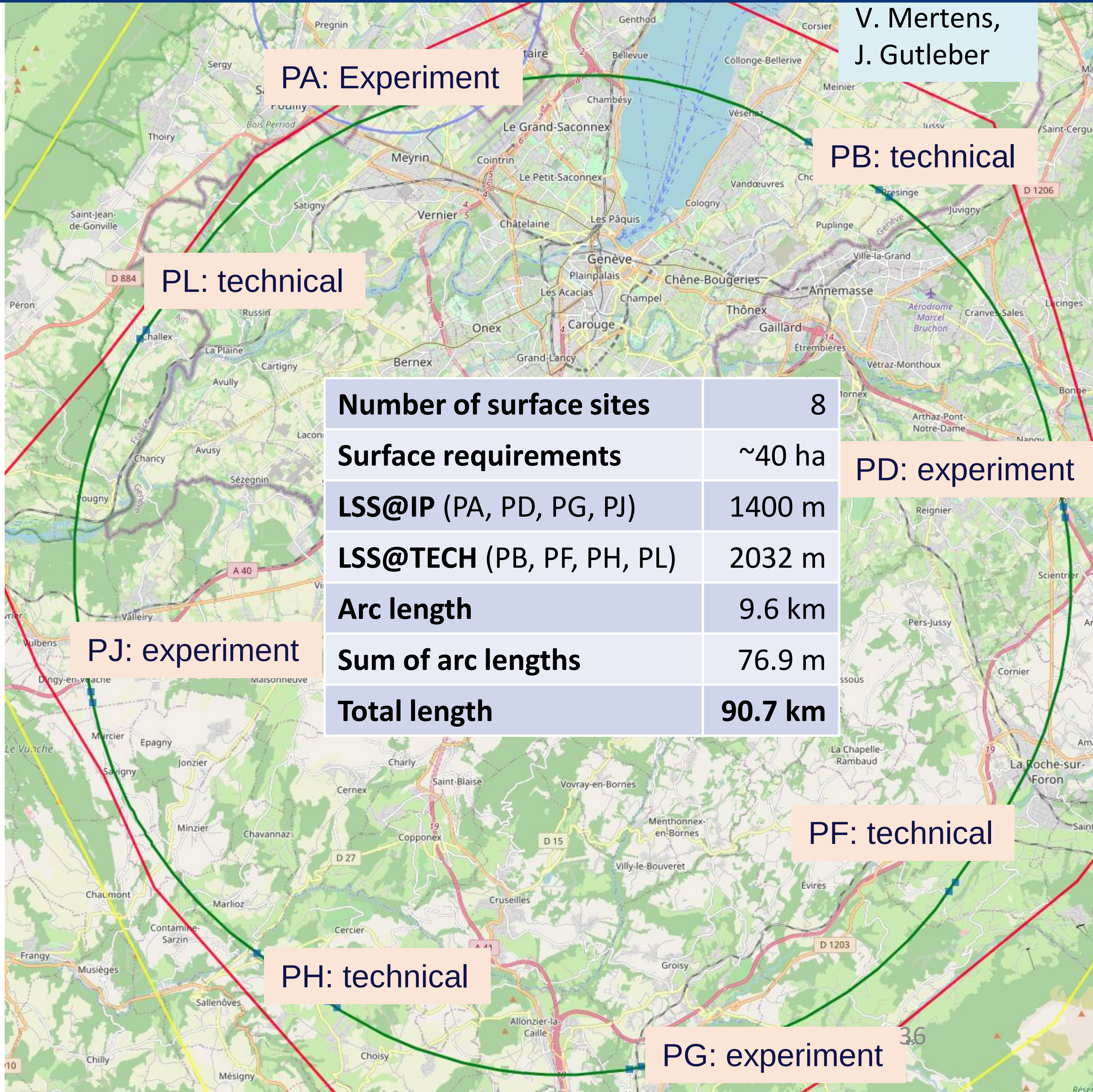
Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

“Avoid-reduce-compensate” principle of EU and French regulations

Overall lowest-risk baseline: 90.7 km ring, 8 surface points,
Whole project now adapted to this placement

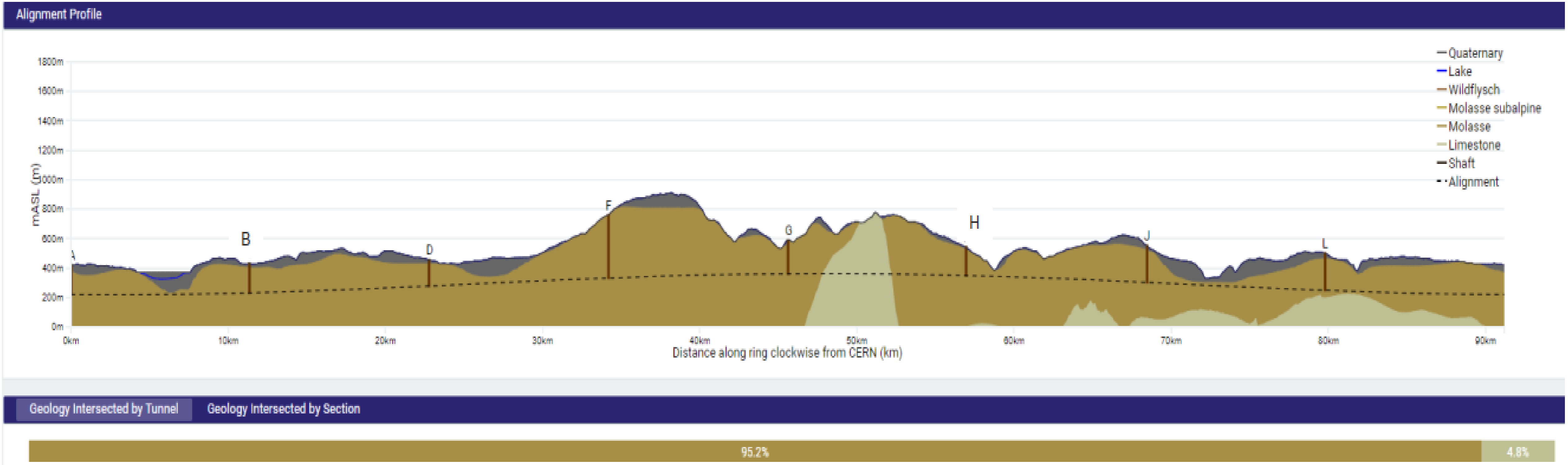


V. Mertens,
J. Gutleber



Number of surface sites	8
Surface requirements	~40 ha
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**

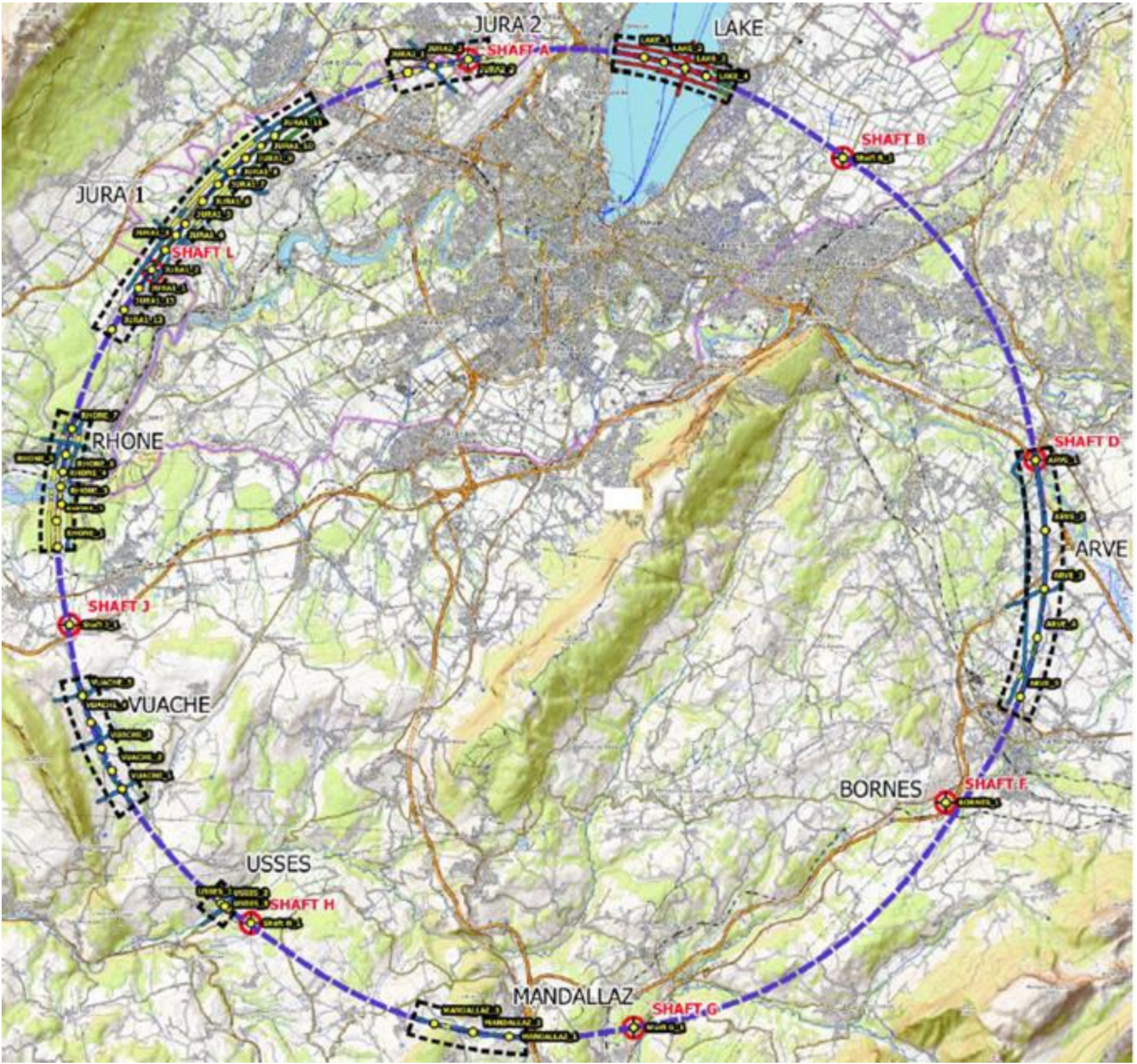
FCC Tunnel Implementation



Tunnel implementation summary

- 91 km circumference
- 95% in molasse geology for minimising tunnel construction risks
- Site investigations in zones where tunnel is close to geological interfaces: moraines-molasse-limestone

Status of Site Investigations



- **Site investigations in areas with uncertain geological conditions:**
  - Optimisation of localisation of drilling locations ongoing with site visits since end 2022.
  - **Alignment with FR and CH on the process for obtaining autorisation procedures. Ongoing for start of drillings in Q2/2024.**
- **Contracts Status:**
  - Contract for engineering services and role of Engineer during works, active since July 2022
  - Site investigations tendering ongoing towards contract placement in December 2023 and mobilization from January 2024.

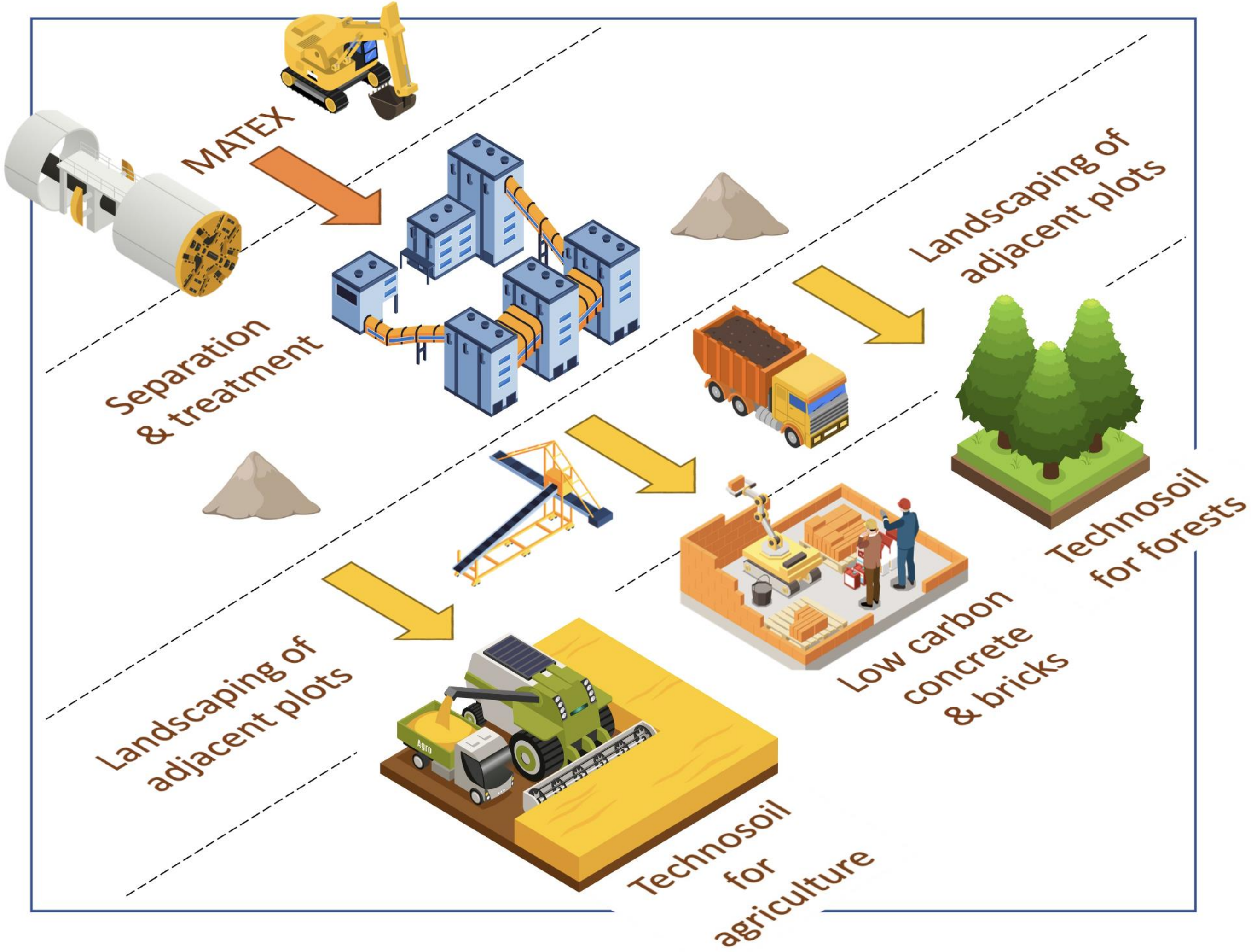

Sondage A89 (2007) incliné de 45° de 125 ml (surface plateforme estimée : 12 x 12 m soit environ 150 m²)


Drilling works on the lake

Excavation Material Management

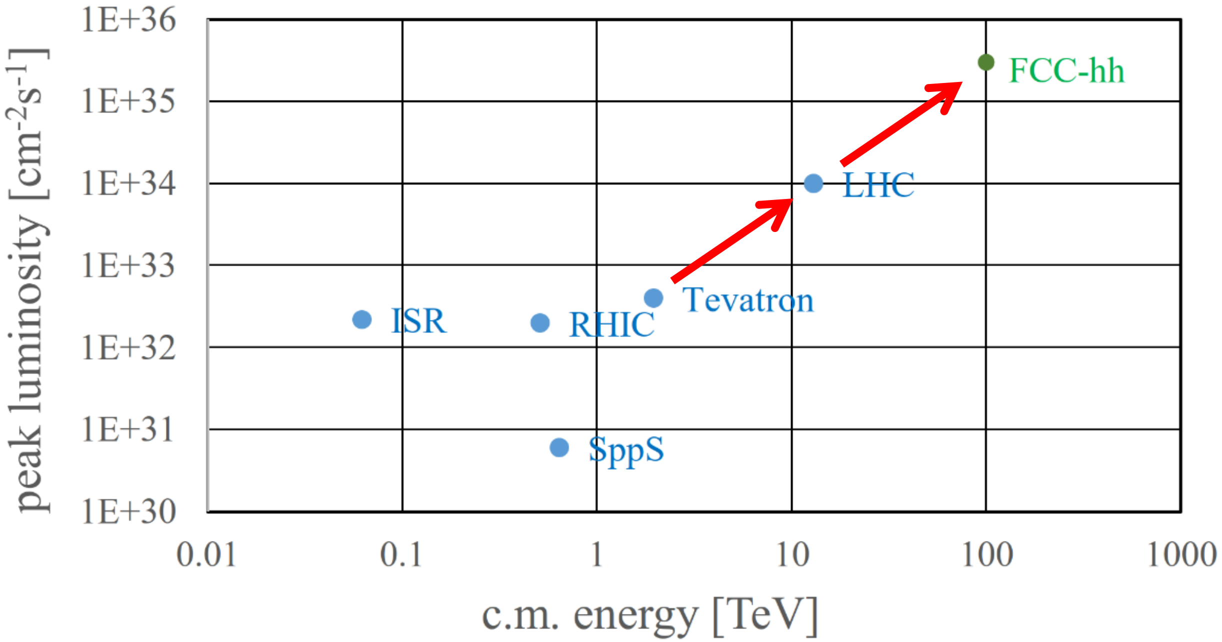
T. Watson

An innovative local approach for excavated materials



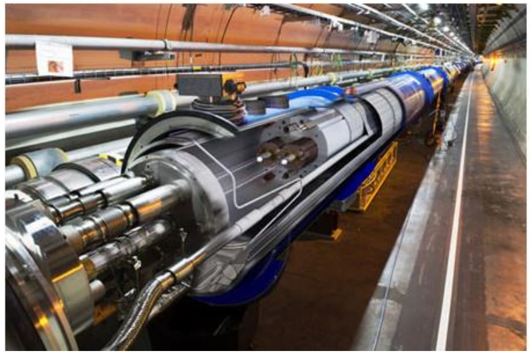
- Excavated material from FCC subsurface infrastructures: 6.5 Mm^3 in situ, 8.4 Mm^3 excavated (bulk factor 1.3)
- **2021-2022: International competition “Mining the Future”**, launched with the support of the EU Horizon 2020 grant agreement 951754, to **find innovative and realistic ideas for the reuse of Molasse** (96% of excavated materials)
- **2023: Definition of the “OpenSky Laboratory” project:**
  - Objective: Develop and test an innovative process to transform sterile “molasse” into fertile soil for agricultural use and afforestation.
  - Duration: 4 years (2024-2027)

FCC-hh: Highest Collision Energies

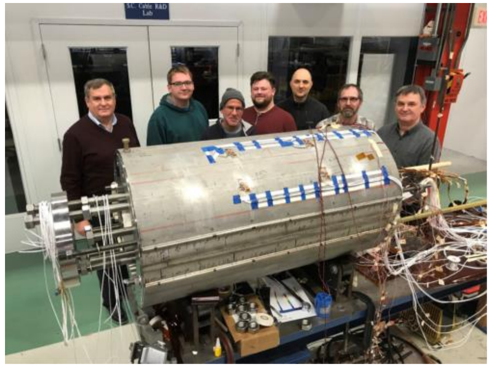


- **Order of magnitude performance increase** in both **energy & luminosity**
- **100 TeV collision energy** (vs 14 TeV for LHC)
- **20 ab^{-1} per experiment collected over 25 years** of operation (vs 3 ab^{-1} for LHC)
- Similar performance increase as from Tevatron to LHC
- **Key technology: high-field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

from
LHC technology
8.3 T NbTi dipole



via
HL-LHC technology
12 T Nb_3Sn quadrupole



FNAL dipole
demonstrator
14.5 T Nb_3Sn

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FCC-hh – Main Machine Parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} cm^{-2}s^{-1}]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

With FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:

- ☐ high-field superconducting magnets: 14 - 20 T
- ☐ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ☐ stored beam energy: ~ 9 GJ → machine protection
- ☐ pile-up in the detectors: ~1000 events/xing
- ☐ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:

- ☐ Direct discovery potential up to ~ 40 TeV
- ☐ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ☐ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, Zγ, μμ)
- ☐ Final word about WIMP dark matter

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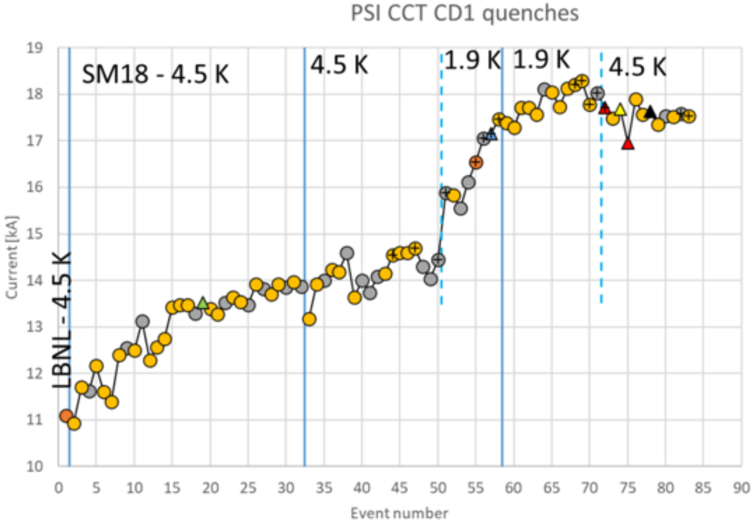
High-field Magnets for FCC-hh: Nb_3Sn & HTS R&D

PSI Nb3Sn CCT «CD1» main test carried out in 2022/23



It trained *A LOT*. **It reached 100% of maximum field at 4.5 K.** No conductor degradation occurred from handling, assembly, powering, or thermal cycling.

Stress-management works, CD1 is a robust magnet.

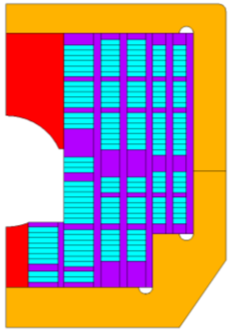
B. Auchmann

Next: FCC-hh SM-CC Demonstrator

Goal: demonstrate robust & cost-efficient Nb3Sn technology for next European Strategy update.

Novel concept: Stress-managed and asymmetric common coils.

D. Araujo



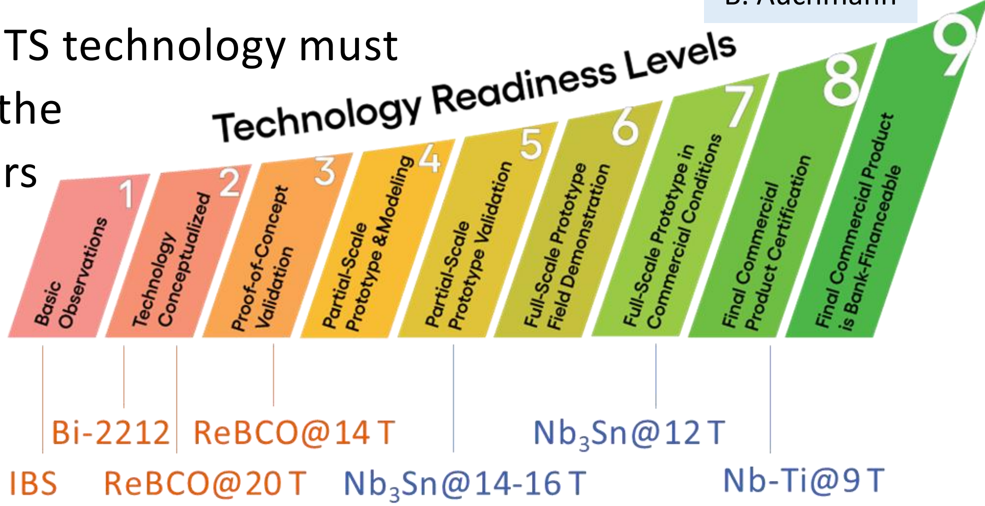
Stainless steel shell
Iron yoke
Coil collar
Former
Non-magnetic poles
Nb_3Sn conductor

B_0 target of 14 T, at T_{op}: 4.2 K
Eng margin of 10%
B_0 short sample @ 1.9 K: 16 T

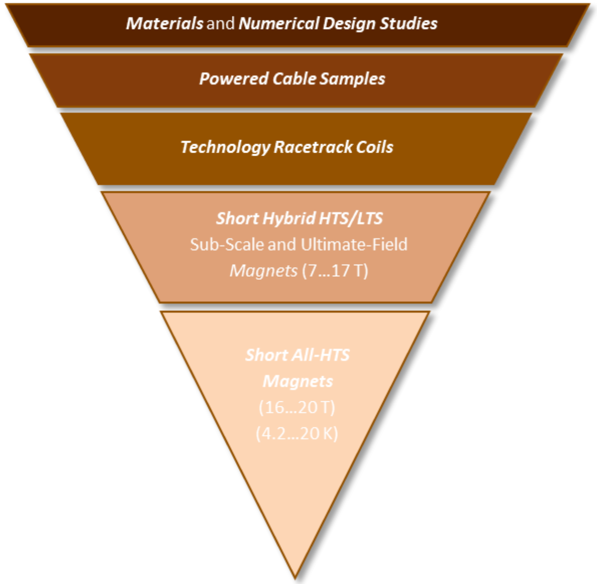
Rough estimates

Bottom line: HTS technology must catch up over the coming 10 years in TRL to LTS

B. Auchmann



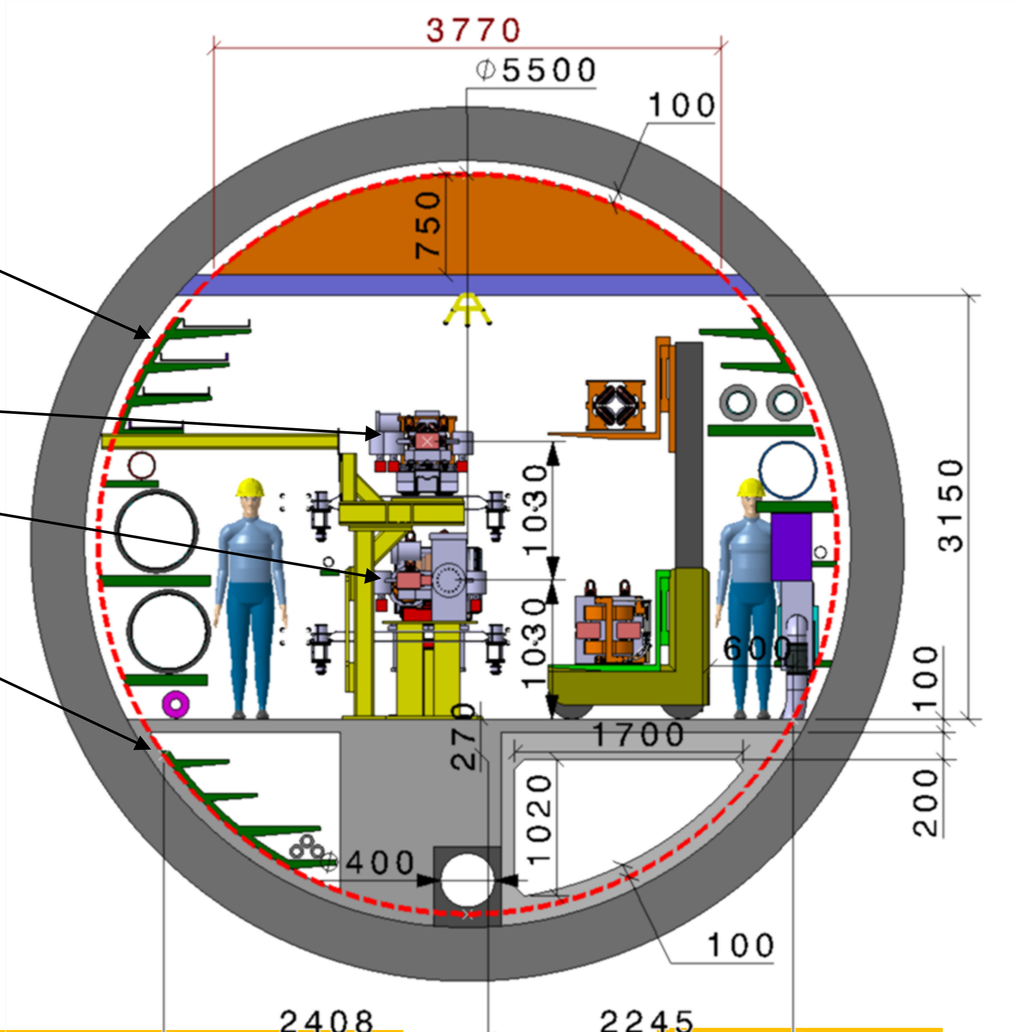
HTS Innovation Funnel for HFM



First deliverable		*#Deliverables / year*
2023	***Materials*** and ***Numerical Design Studies***	100s
2023	***Powered Cable Samples***	10
2024	***Technology Racetrack Coils***	2
2025	***Short Hybrid HTS/LTS*** Sub-Scale and Ultimate-Field *Magnets* (7…17 T)	1
	Short All-HTS Magnets (16…20 T) (4.2…20 K)	

Regular Arc Tunnel Cross-section & Element Integration

FCC-ee



Cable trays:
Fibre optic
LV distribution
Control cables

Booster ring

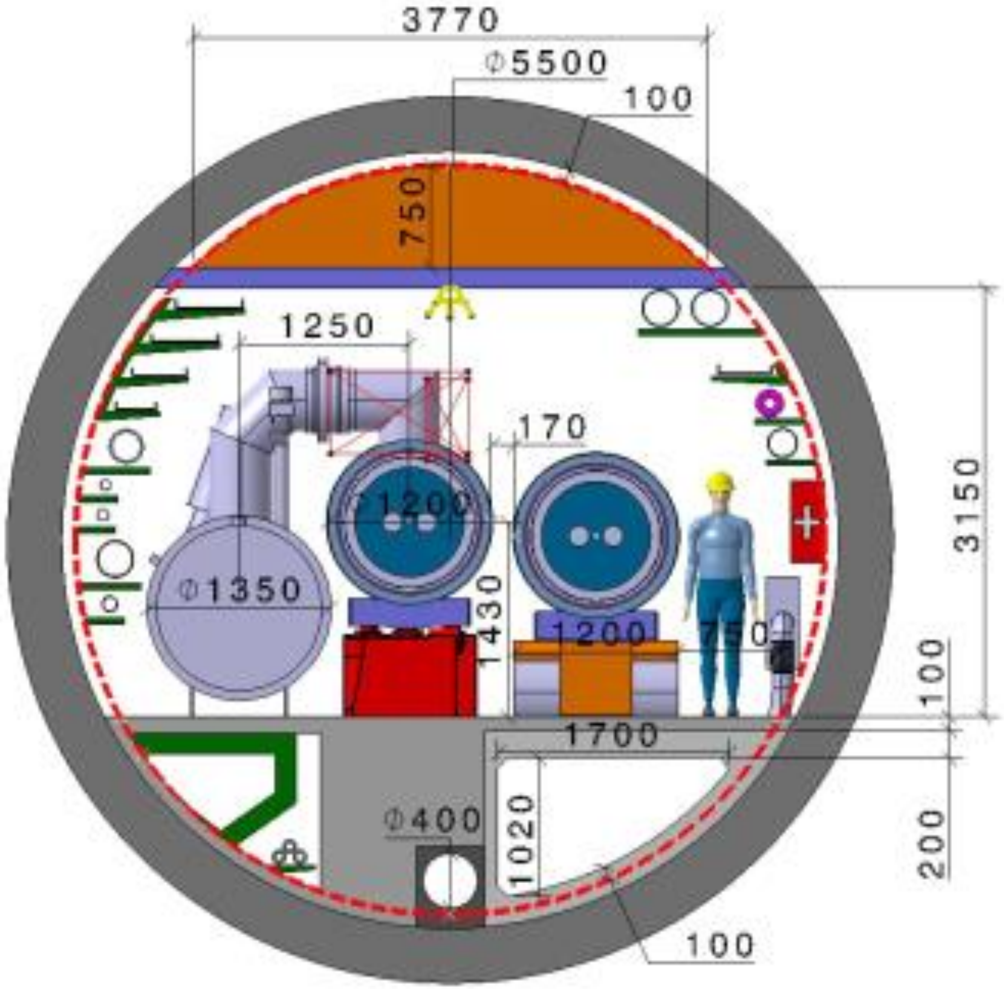
Collider ring

DC cable trays
HV cable

Main ring below of booster ring
Main ring and booster ring 1.03 m apart

Collider Center

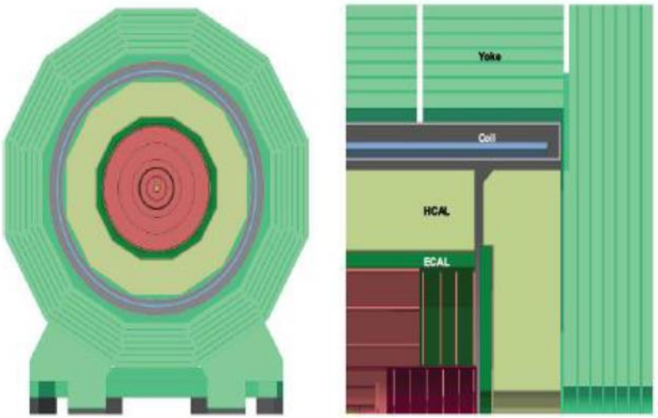
FCC-hh



Collider Center

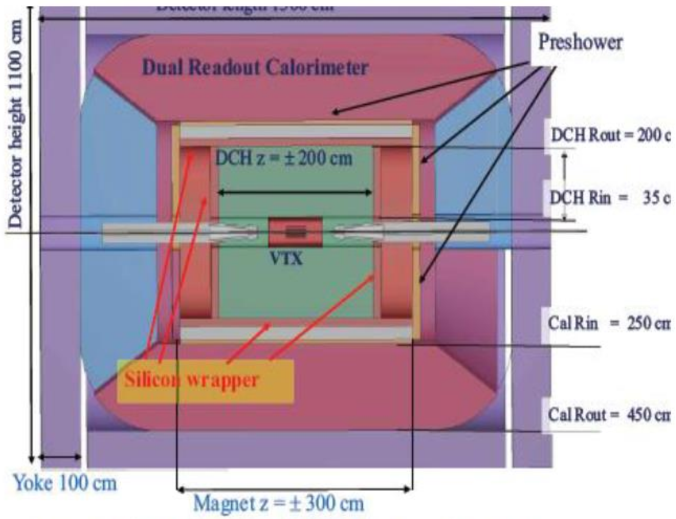
Detectors Under Study for FCC-ee

CLD



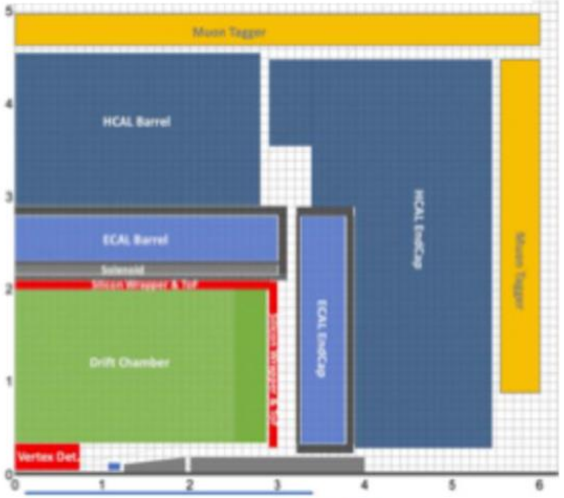
conceptually extended from the CLIC detector design
- full silicon tracker
- 2T magnetic field
- high granular silicon-tungsten ECAL
- high granular scintillator-steel HCAL
- instrumented steel-yoke with RPC for muon detection

IDEA



- explicitly designed for FCC-ee/CepC
  - silicon vertex
  - low X_0 drift chamber
  - drift-chamber silicon wrapper
  - MPGD/magnet coil/lead preshower
  - dual-readout calorimeter: lead-scintillating/ cerenkhov fibers

Noble Liquid ECAL



- explicitely designed for FCC-ee, recent concept, under development
- silicon vertex
- Low X_0 drift chamber
- Thin Solenoid before the Calorimeter
- High Granularity Liquid Argon Calorimetry

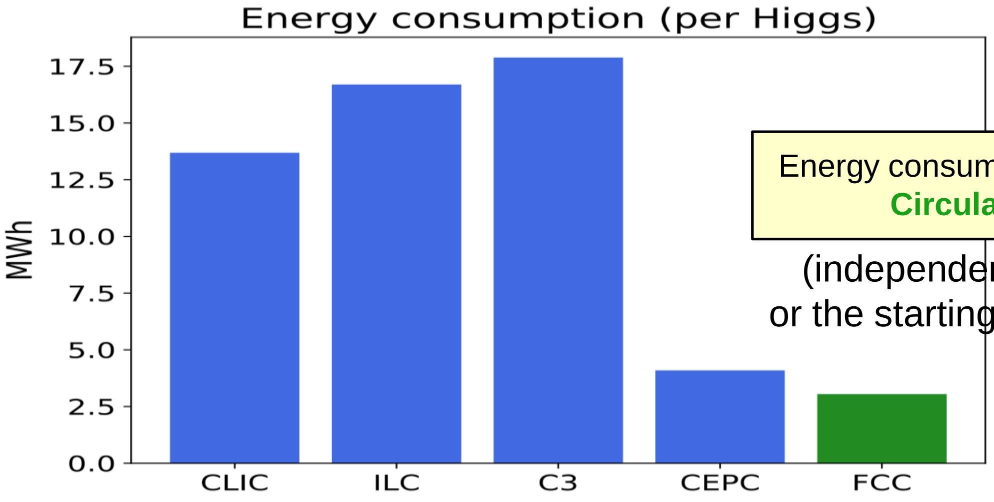
But several other options like Crystal Calorimetry (active in US, Italy), are under study
(similarly for tracking, muons and particle ID)
and Time Projection Chamber (TPC) of ILD
With potentially 4 experiments, many complementary options will be implemented,
Definitely a place to contribute

Energy and Carbon Footprint

- **Our first responsibility (as particle physicists) is to do the maximum of science**
  - **With the minimal energy consumption and the minimal environmental impact for our planet**
    - **Should become one of our top-level decision criteria for design, choice and optimization of a collider**

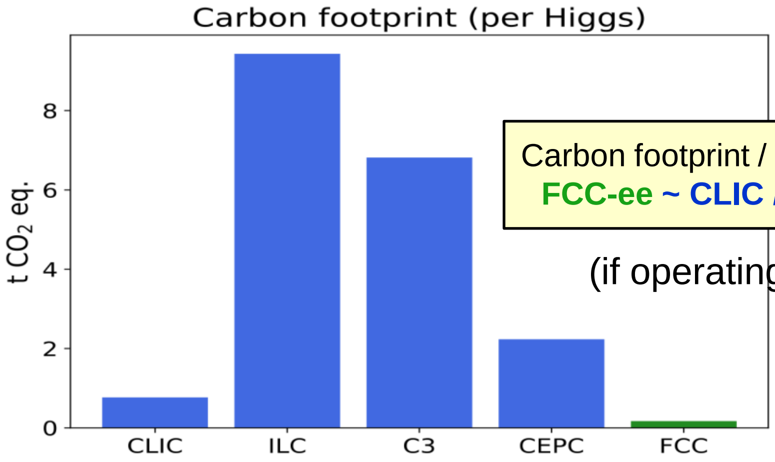
- **All Higgs factories have a "similar" physics outcome**
  - **Natural question: what is their energy consumption or carbon footprint for the same physics outcome?**
    - **Circular colliders have a much larger instantaneous luminosity and operate several detectors**
    - **FCC-ee is at CERN, where electricity is already almost carbon-free (and will be even more so in 2048)**

arXiv:2208.10466



Energy consumption / Higgs with 2IP
Circular ~ Linear / 5

(independently of the location
or the starting time of the collider)



Carbon footprint / Higgs with 2IP
FCC-ee ~ CLIC / 5 ~ ILC / 50

(if operating today)

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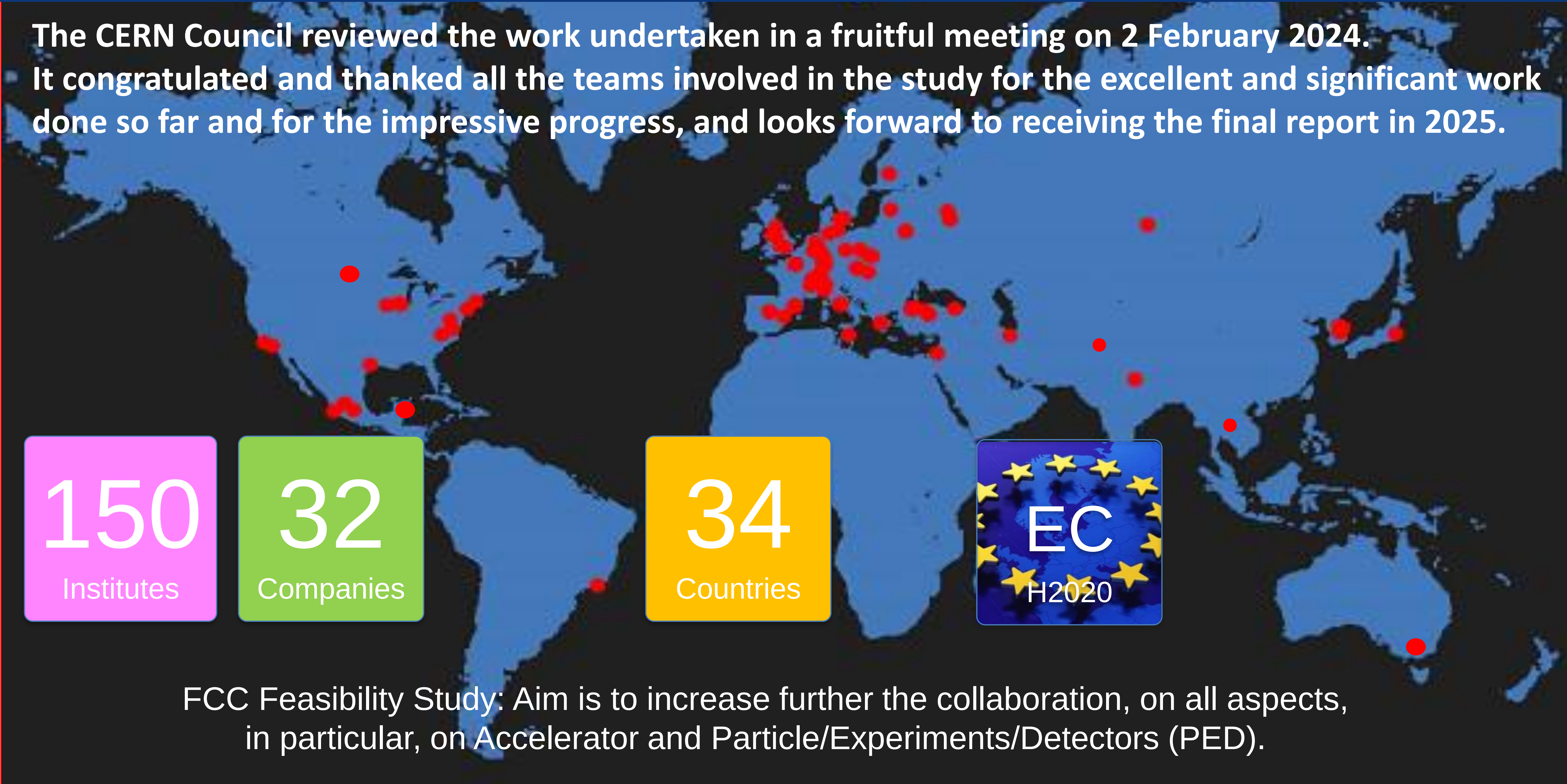
Status of FCC Global Collaboration



The CERN Council reviewed the work undertaken in a fruitful meeting on 2 February 2024.
It congratulated and thanked all the teams involved in the study for the excellent and significant work done so far and for the impressive progress, and looks forward to receiving the final report in 2025.

150
Institutes

32
Companies

34
Countries

EC
H2020

FCC Feasibility Study: Aim is to increase further the collaboration, on all aspects, in particular, on Accelerator and Particle/Experiments/Detectors (PED).

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FCC Week 2023
London, UK

473 participants

362 in person and
111 remote

FCC Week 2024
San Francisco, USA
10-14 June 2024

Courtesy P. Charitos

FCC Summary & Outlook

We now know much about the **Universe**, using increasingly larger and more complex machines. There remain many very **interesting and unanswered questions** in particle physics to be solved.

CERN is the right place for the next large accelerator.

The **first stage of FCC could be approved within a few years after the next European Strategy Update**, if the latter is supportive. Following **approval by the CERN Council, tunnel construction could then start in the early 2030s** and **FCC-ee physics programme could begin in the second half of the 2040s**, a few years after completion of the HL-LHC physics runs, expected by around 2040.

Long-term goal: **world-leading HEP infrastructure for 21st century** to push particle-physics **precision and energy frontiers** far beyond present limits.

We are counting on the **scientists and engineers of the future** to make the project a success for the exploration of the **<u>fundamental laws and building blocks of the Universe</u>**.

Video - Designing the Future Circular Collider (FCC)