The Future Circular Collider (FCC) at CERN

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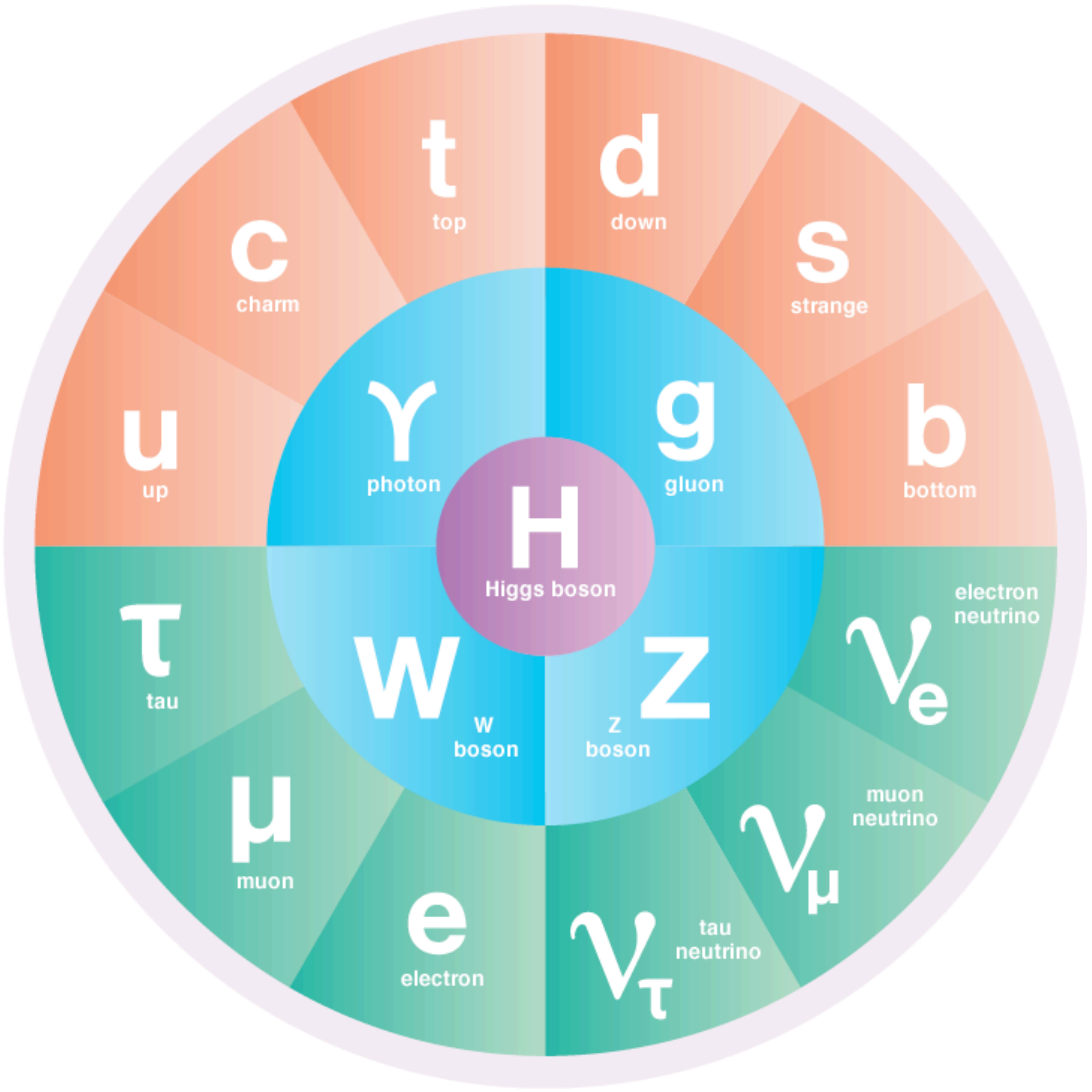
The Standard Model of particle physics

In constant evolution hand in hand with the available technology

- Starts in the 70s
  - Neutral currents in Gargamelle (CERN) in 1973
  - Charmed particles (BNL, SLAC) in 1974-76
- Since then:
  - we have discovered a collection of particles and expanded our understanding of electroweak and strong interactions
  - Possible by advances in technology and increasing accelerator energies

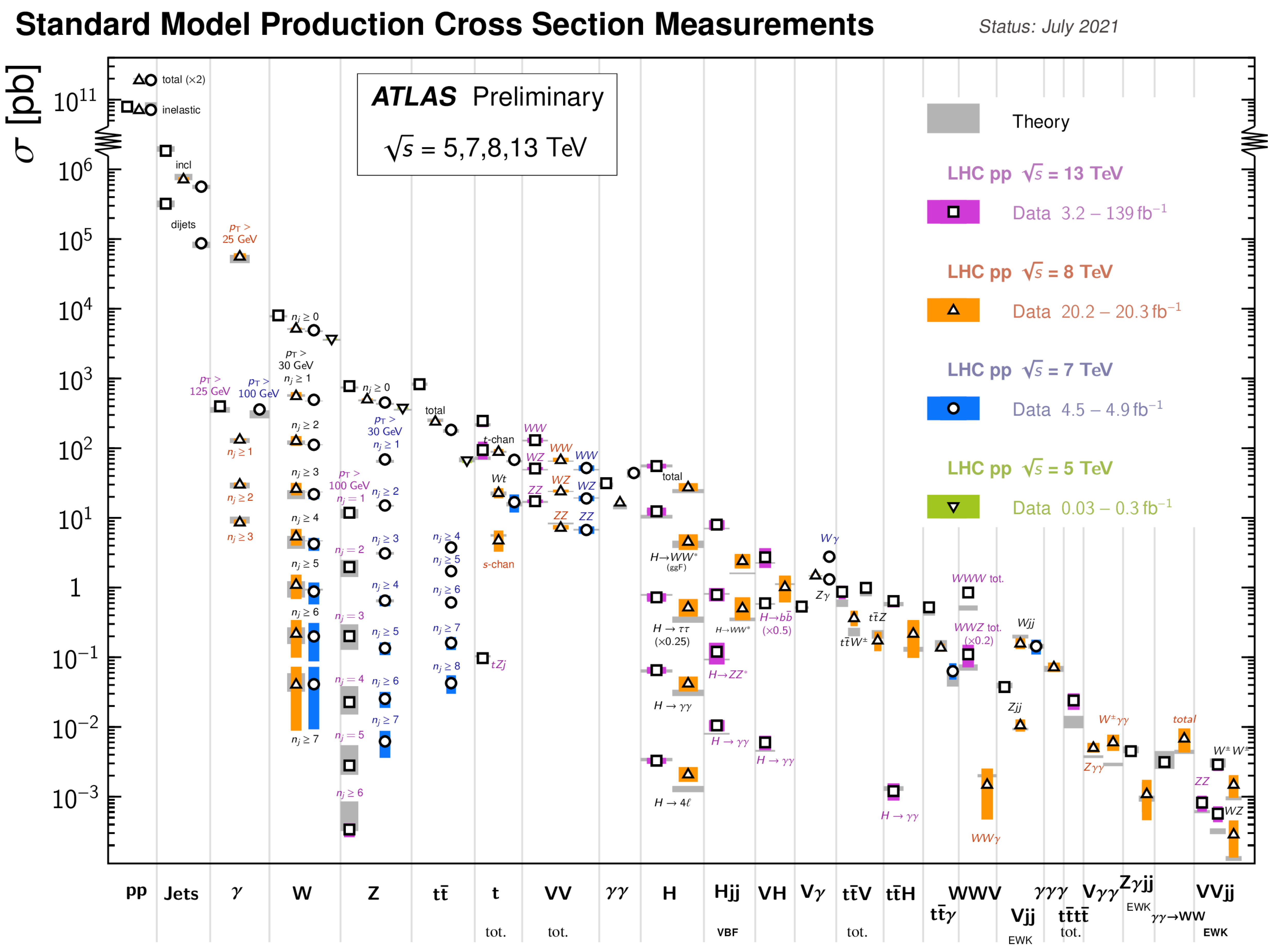


- The LHC has been operative since 2009
- About to start the last run before its high-lumi upgrade (Run-3)
- Next year we will celebrate the 10th anniversary of the discovery of the Higgs boson

Time to take stock of the situation

Before Run-3

- The general-purpose detectors at the LHC (ATLAS and CMS) have produced more than 1,000 papers each (and counting) LHCb is on 600
- We found the Higgs boson: First of its kind, scalar, neutral boson
- Thorough testing of the SM
  - No significant deviations from the SM have been observed
  - After the Higgs no other new particles have been found



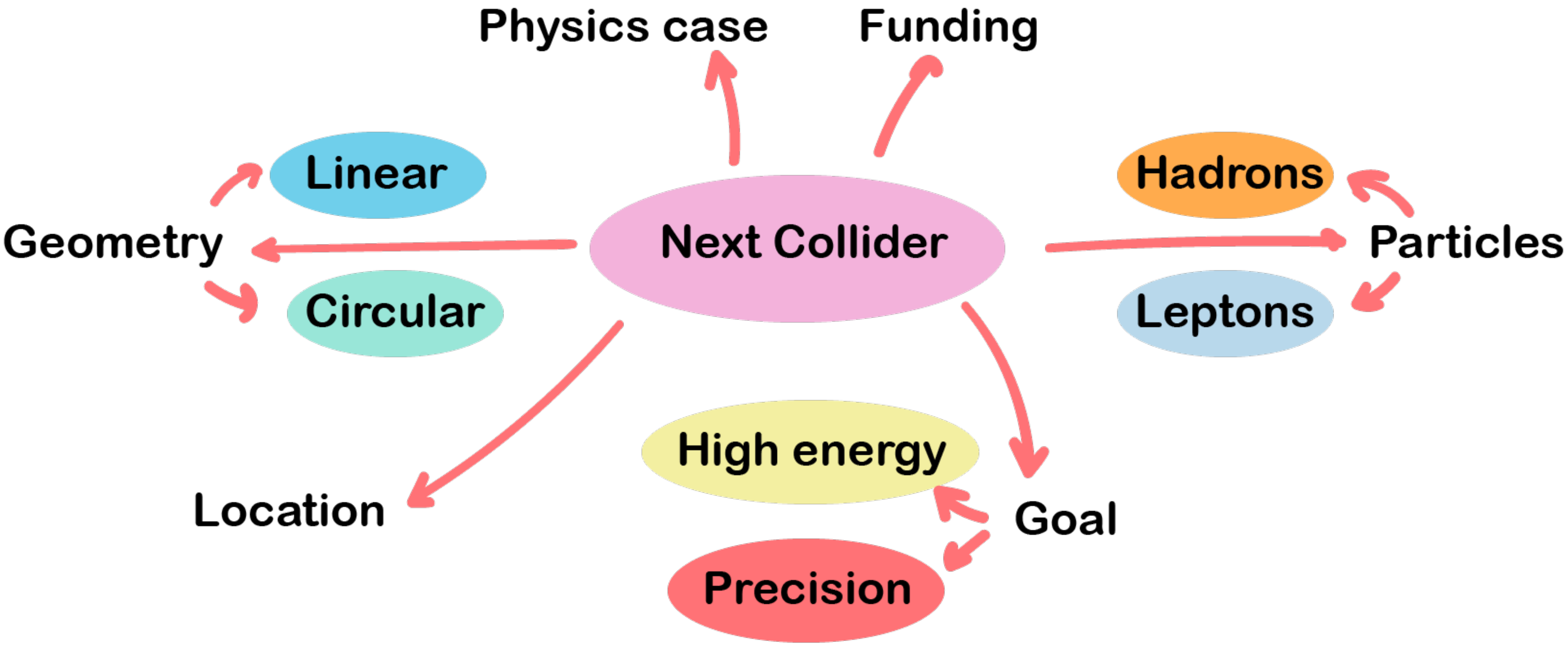
- The discovery of the Higgs boson at the LHC closes a central chapter of the Standard Model, and poses new questions
- Other have been open for a while

- We can only describe 3/4 forces
- 3 generations of matter, unexplained mass hierarchy
- Neutrino masses
- Matter-antimatter unbalance of the Universe
- Dark Matter and Dark Energy
- Theoretical holes and discrepancies solved by fine-tuning in the SM

- **The answer will be found on energy- and intensity-frontier colliders**
- **It is time to plan the next facility**

What are the options?

After the LHC its upgrade, the HL-LHC



- For the first time we have no clear energy scale to target
- We have no choice but to go for something versatile, broad, and as powerful as possible

- We still have a new particle that could help chart future explorations!

The European Strategy for Particle Physics

2020 Update

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

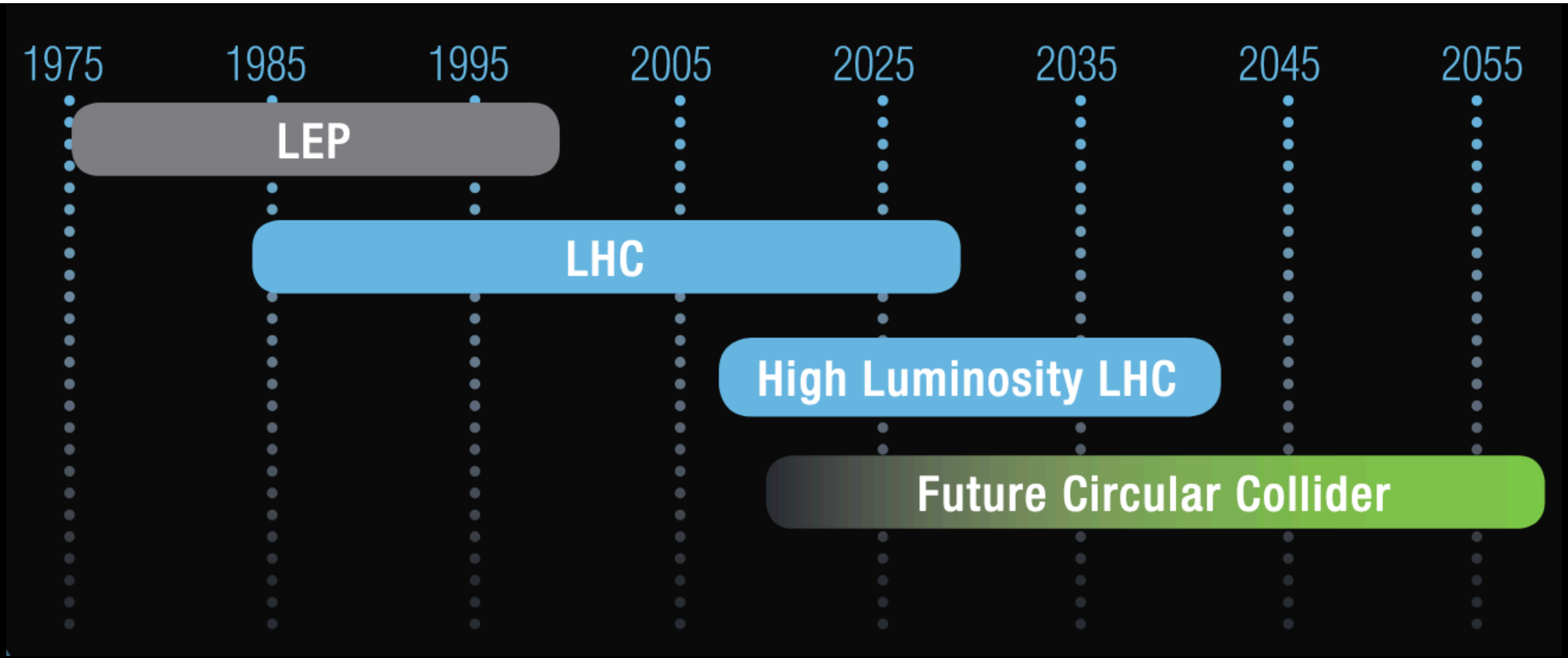
→ launch of Future Circular Collider Feasibility Study in summer 2021

http://europeanstrategy.cern/home

What is the FCC?

The Future Circular Collider (FCC) integrated program

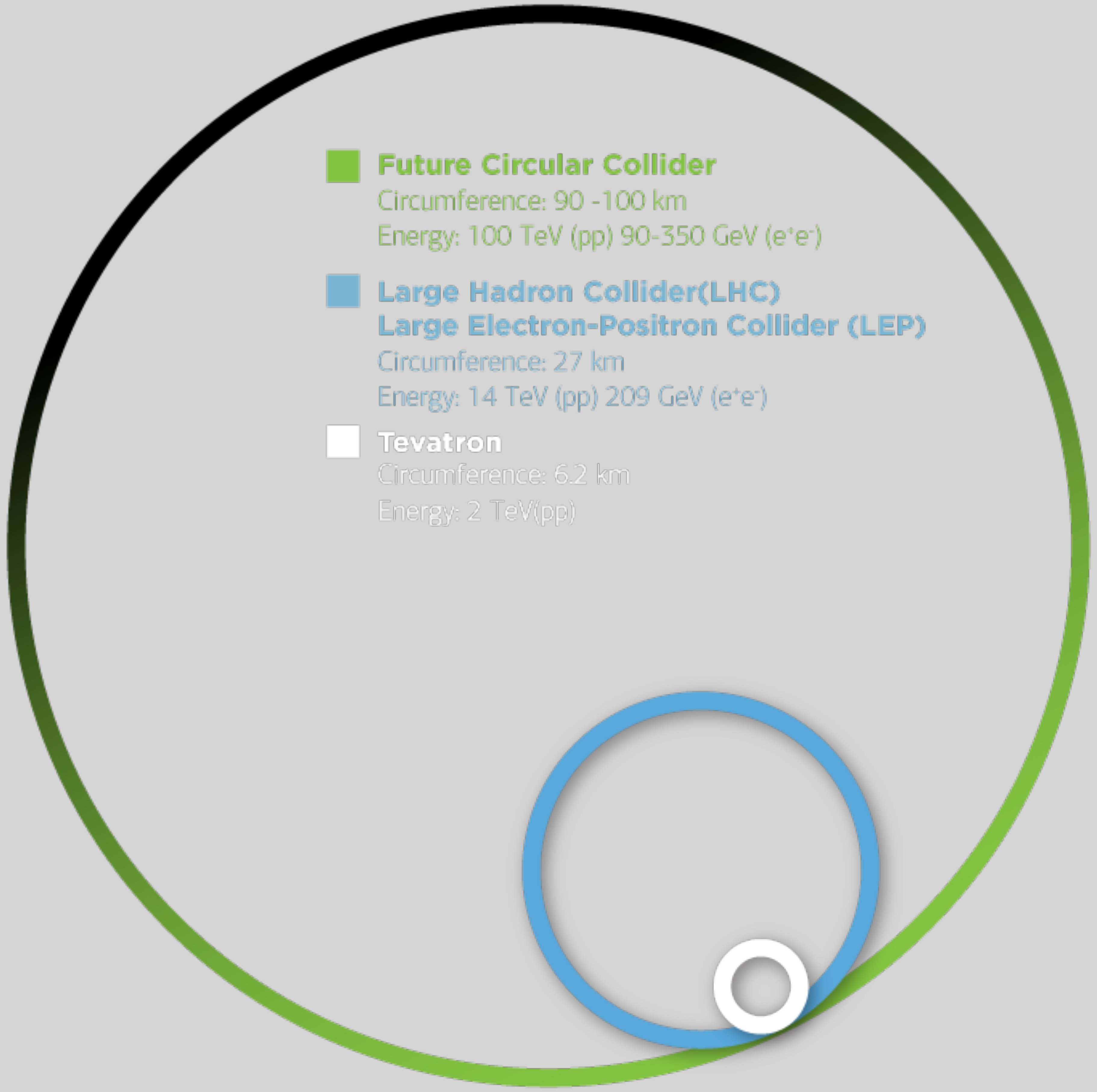
- Proposed post-LHC high-energy frontier circular colliders at CERN
- A comprehensive, cost-effective program maximizing physics opportunities inspired by the successful LEP – LHC (1976-2038?) program
  - Providing a seamless continuation after it.



What is the FCC?

The Future Circular Collider (FCC) integrated program

- One tunnel of ~100 Km of circumference, two stages:
  - **Stage 1:** FCC-ee (Z, W, H, tt) as first generation Higgs EW and top factory at high luminosities
  - **Stage 2:** FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options

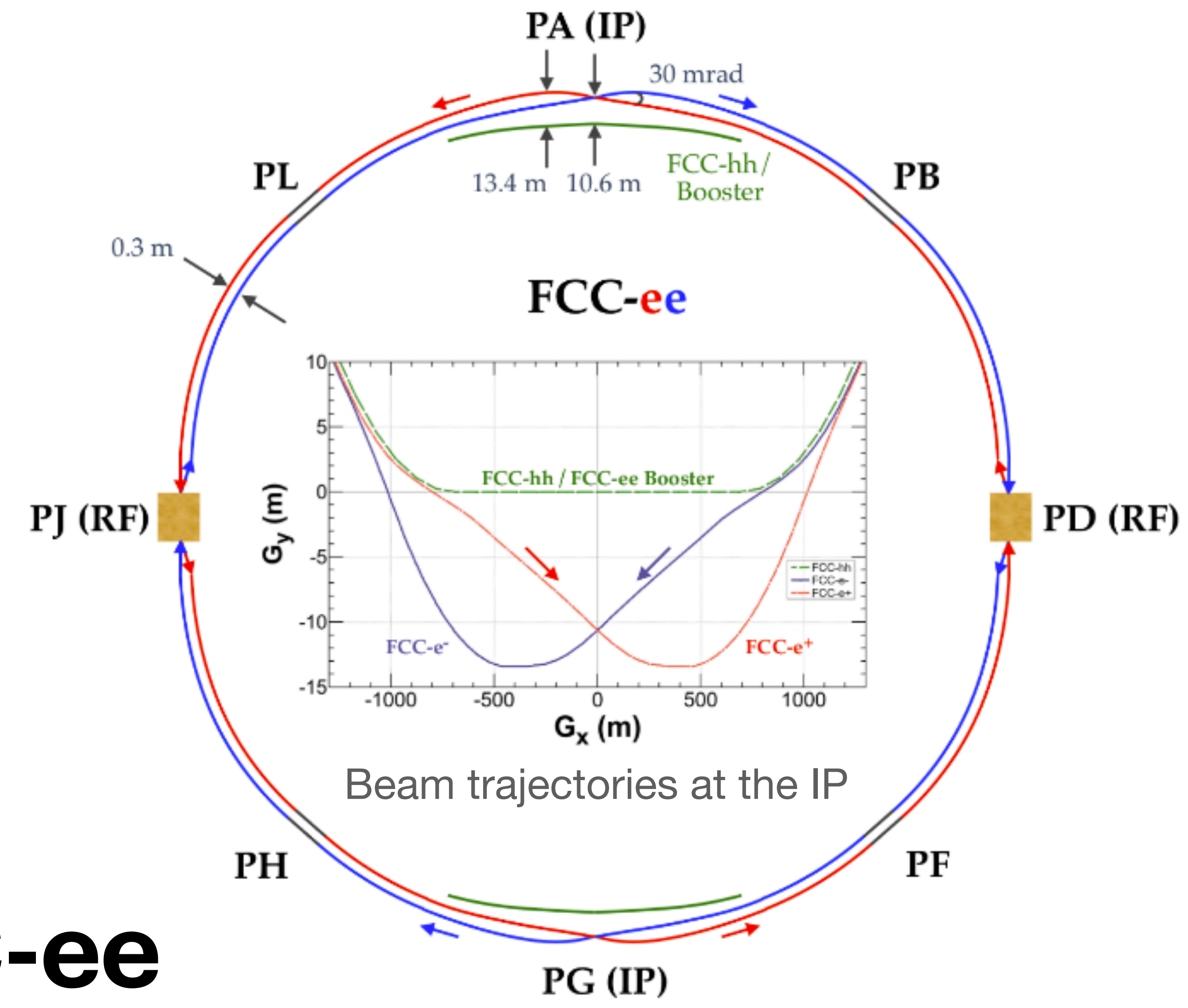



LHC
SWITZERLAND
FRANCE
FCC

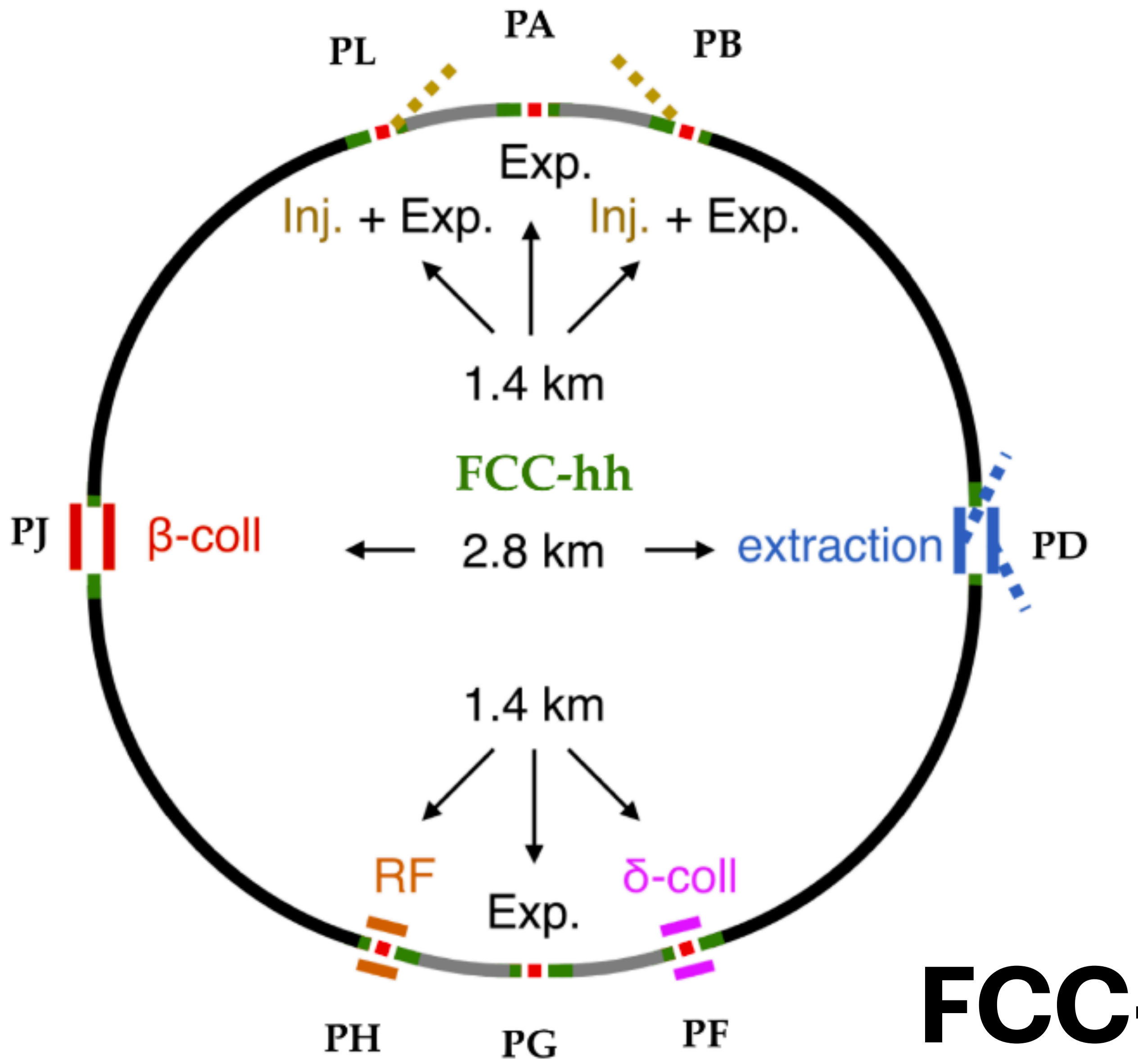
Complementarity: infrastructure

FCC-ee/-hh

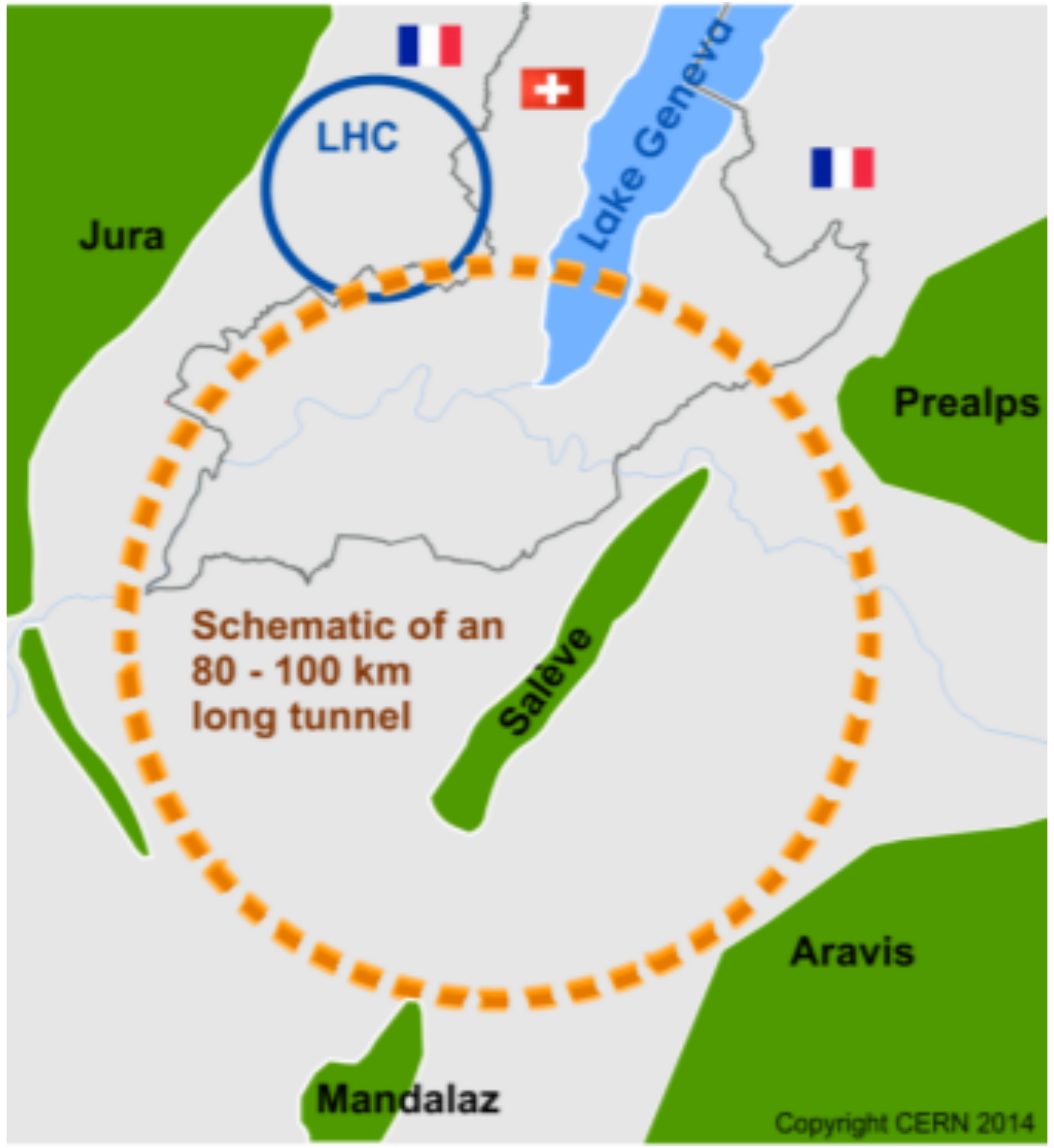
- Sequential implementation
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure
- The FCC-ee booster footprint coincides with that of the FCC-hh



FCC-ee



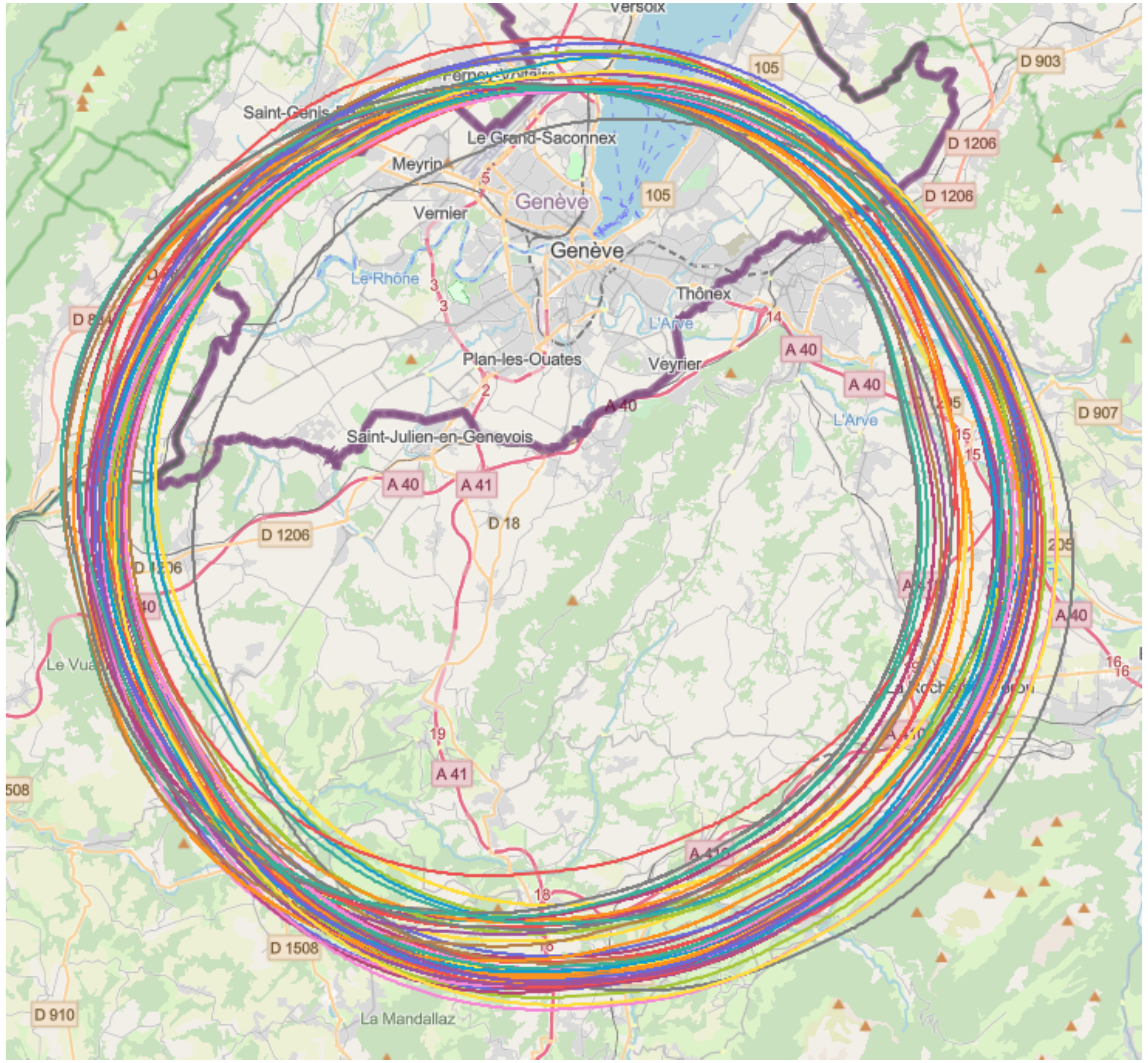
FCC-hh



Collider placement optimisation

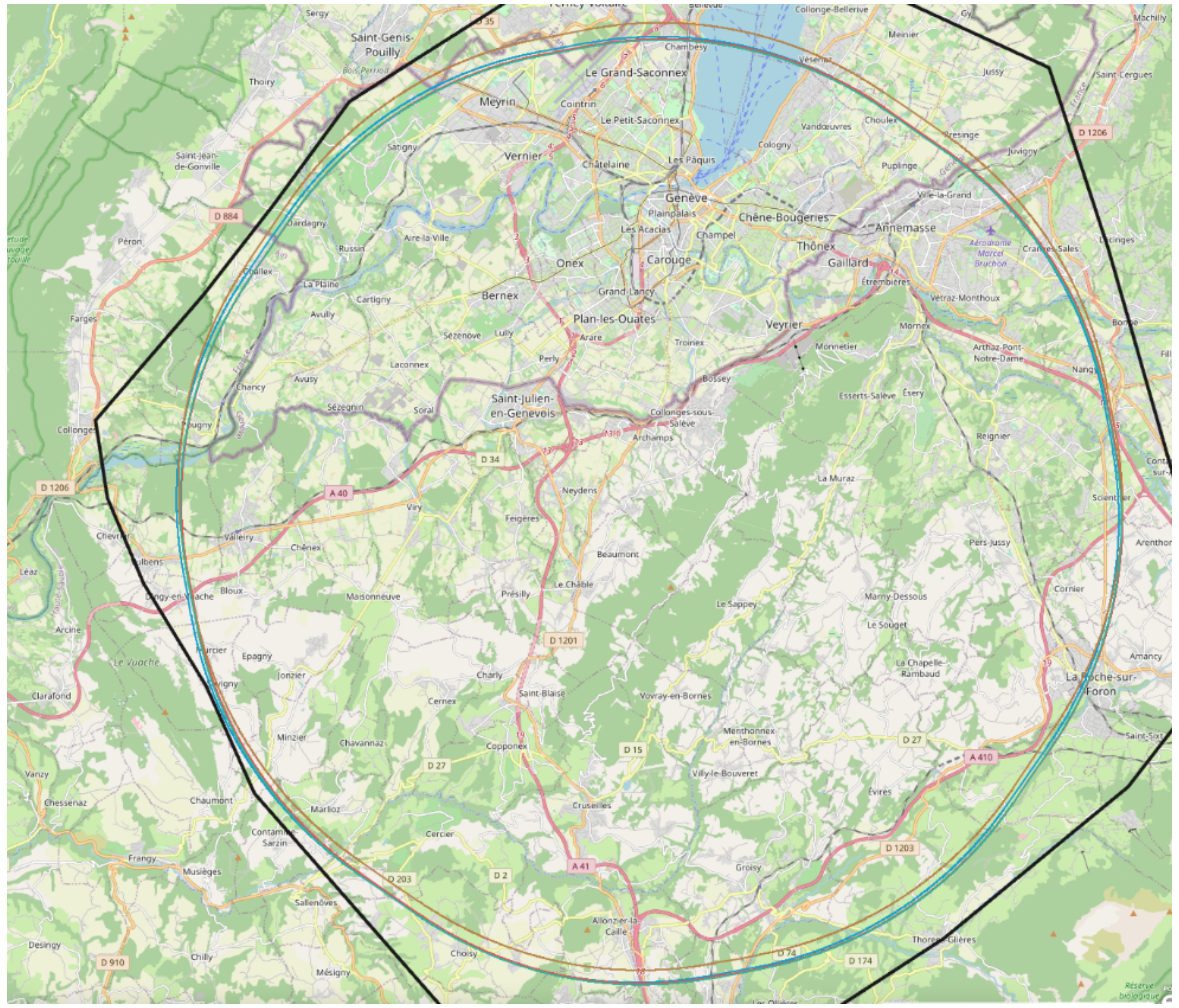
Following European and local regulatory frameworks

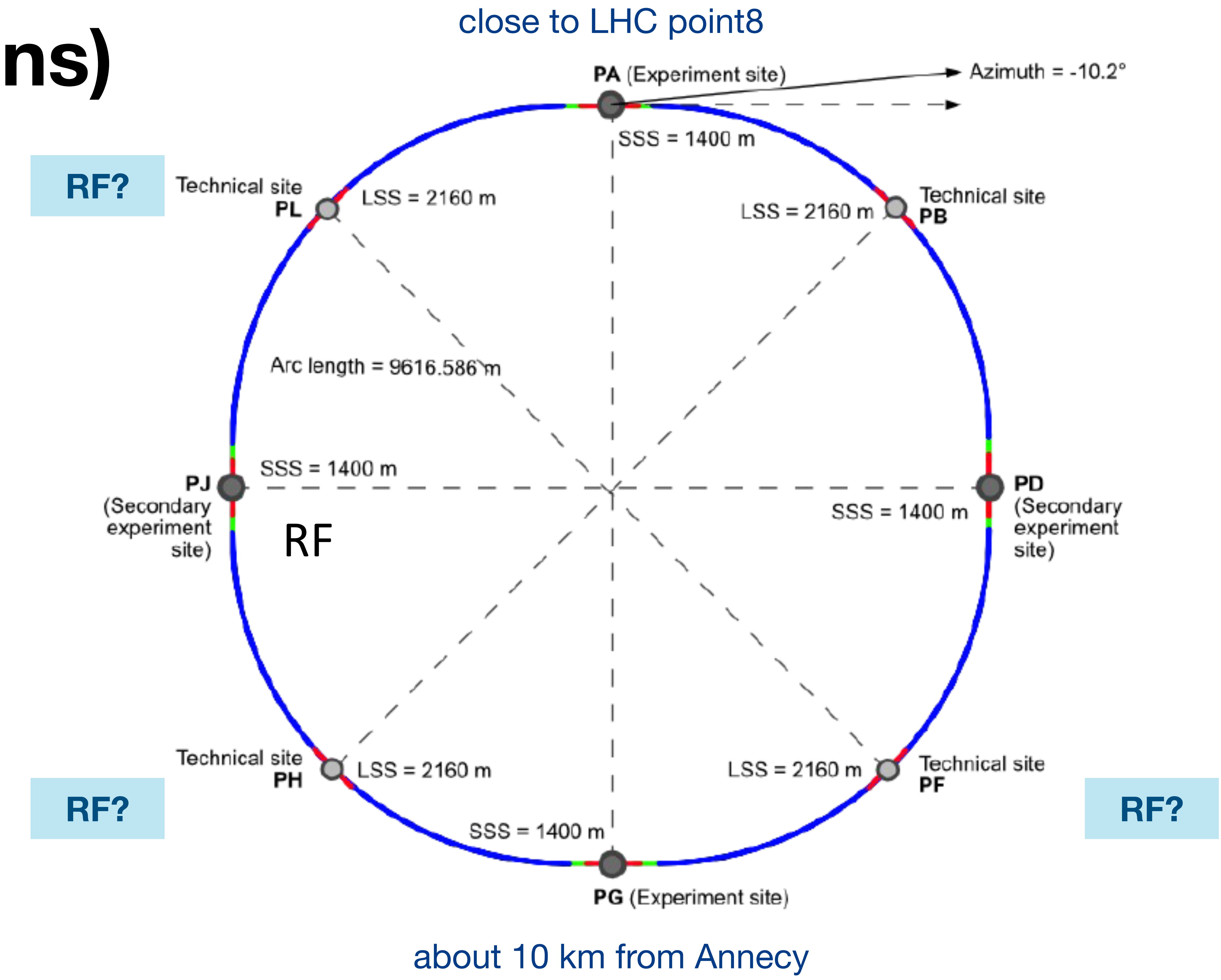
- Set of requirements and constraints, such as:
    - civil engineering feasibility and subsurface constraints
    - territorial constraints at surface and subsurface
    - nature, accessibility, technical infrastructure and resource needs and constraints
    - economic factors related to regional developments
- collaborative effort by technical experts at CERN, consultancy companies and government notified bodies



New FCC layout

baseline layout (2 fallback solutions)



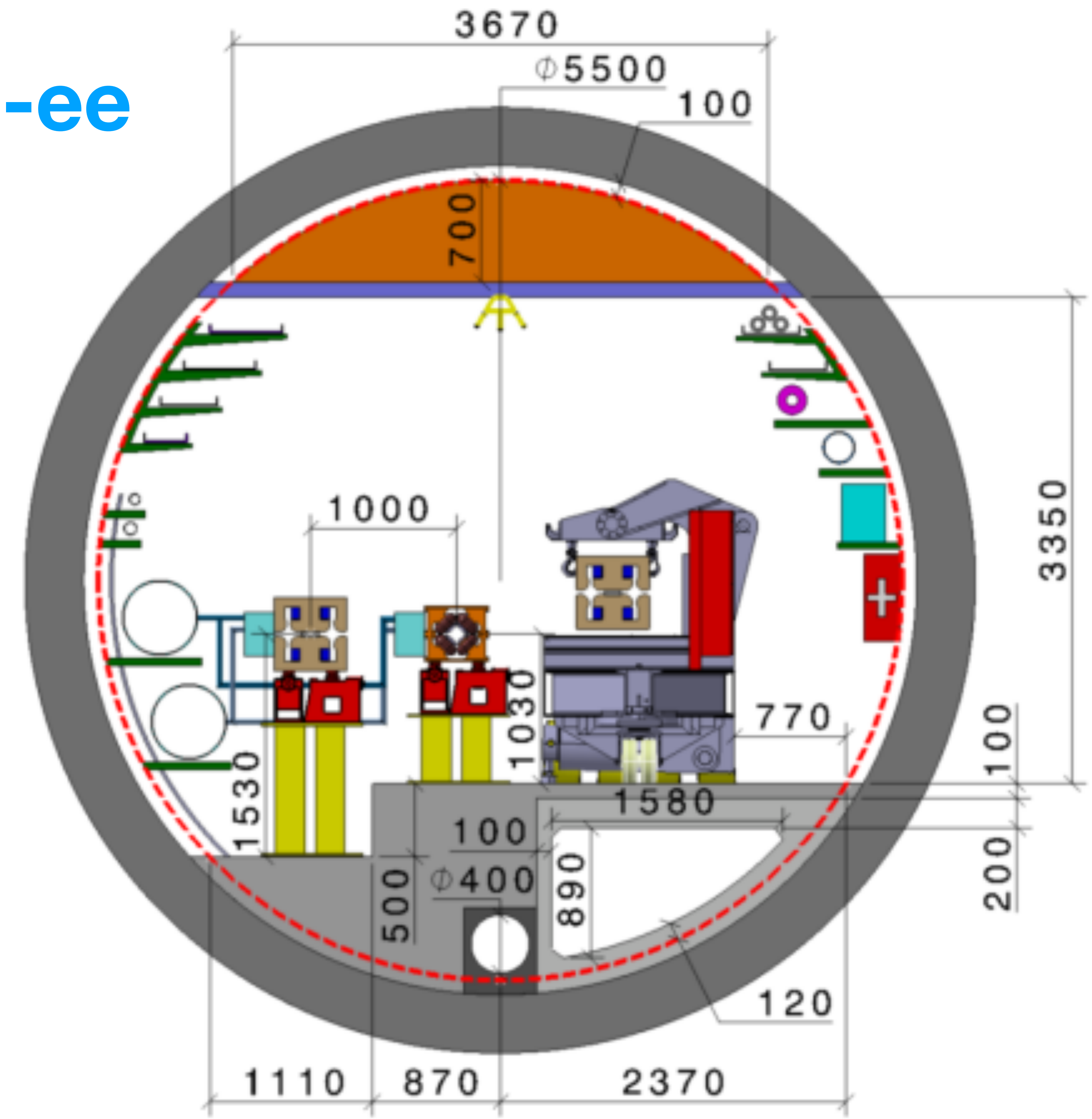


- 8 pits (was 12) total circumference of 91.173 km (was 97km in CDR, cost savings, luminosity reduced by ~10%)
- FCC-ee 2 or 4 interaction points, FCC-hh 4 IPs

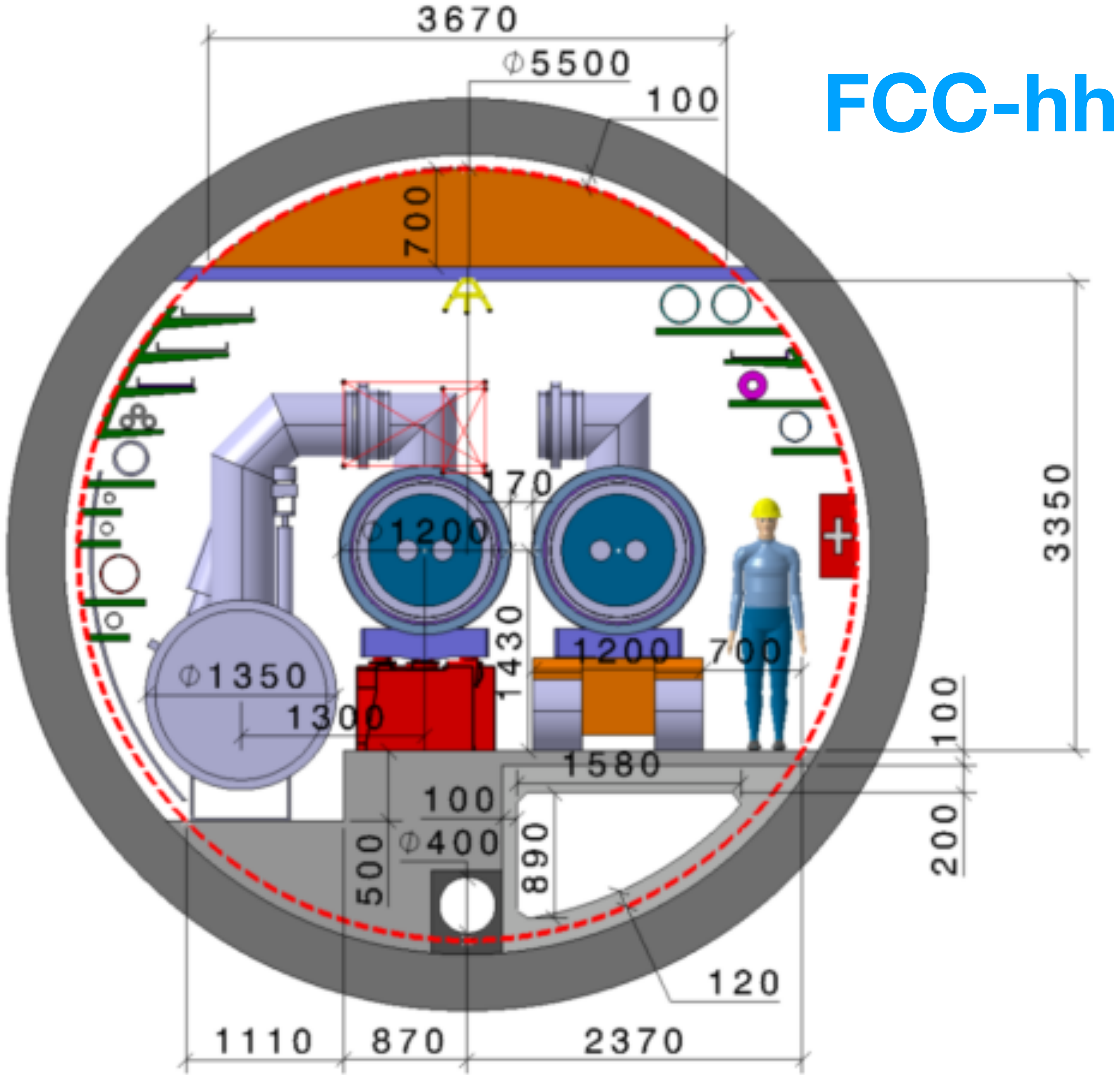
FCC tunnel

5.5m inner diameter

FCC-ee

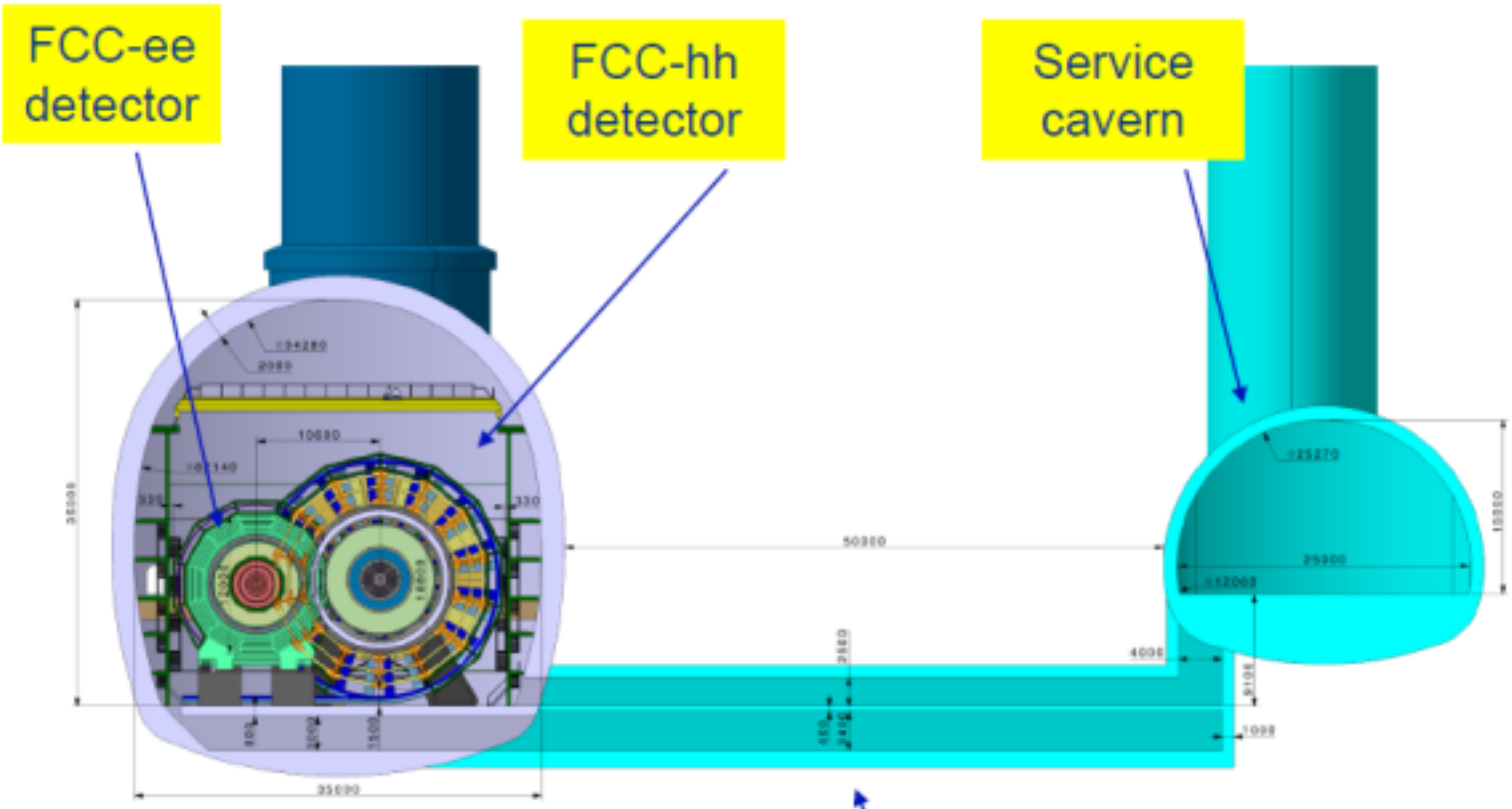


FCC-hh

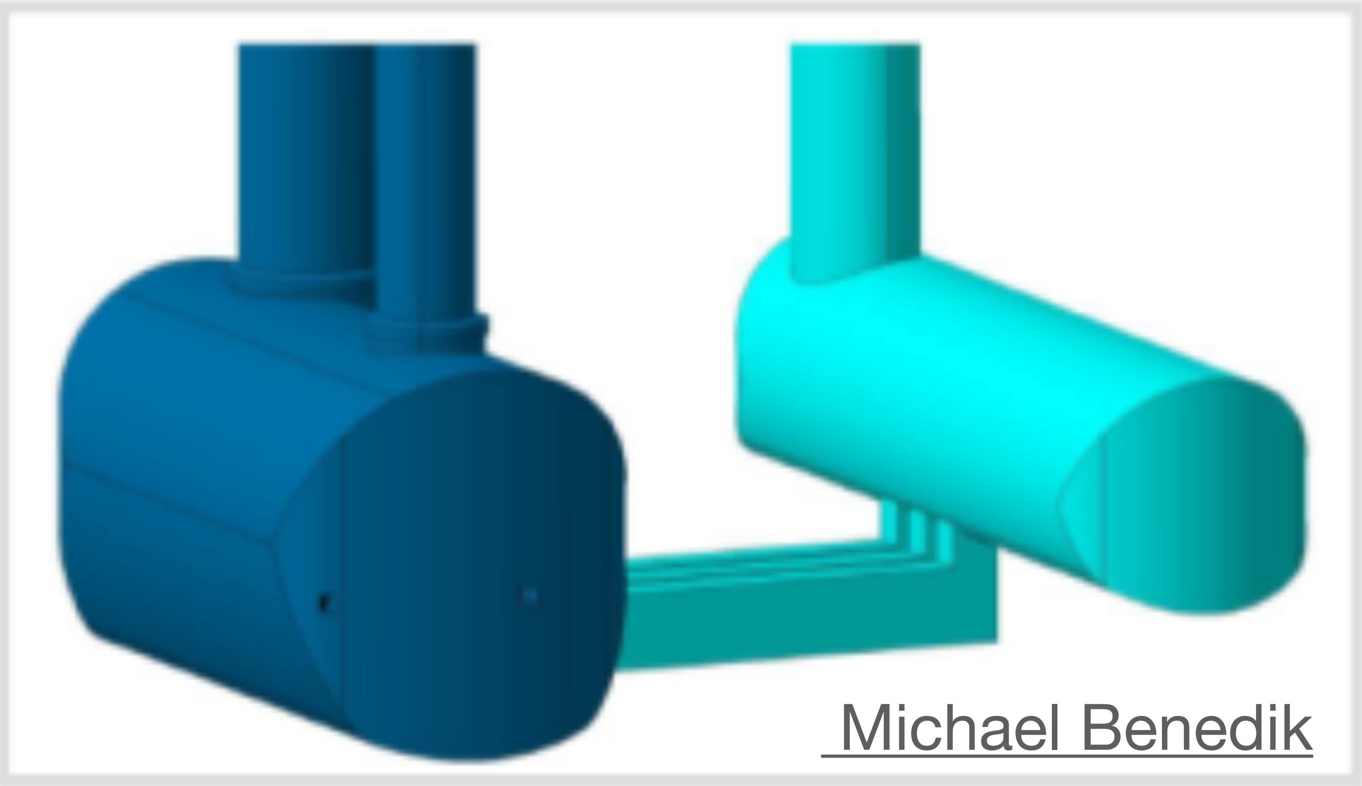


Common experimental points

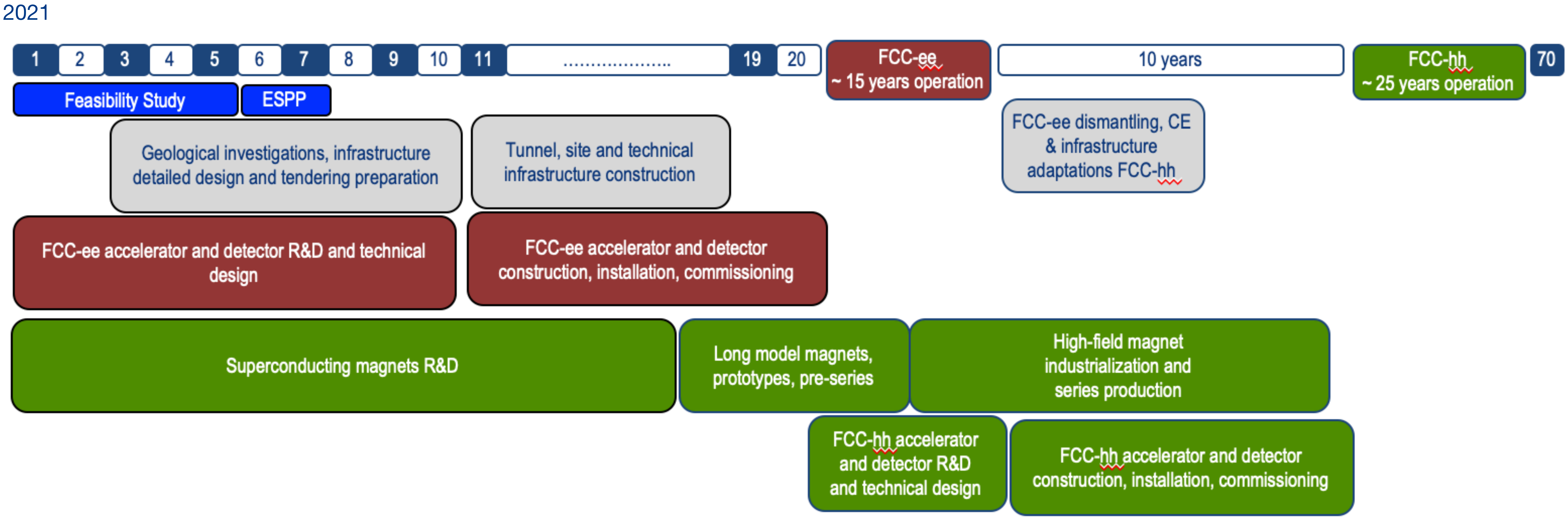
Distance between detector cavern and service cavern 50 m.
Strayfield of unshielded detector solenoid < 5mT.



Preliminary design of access and cable paths



Timeline of the FCC integrated programme



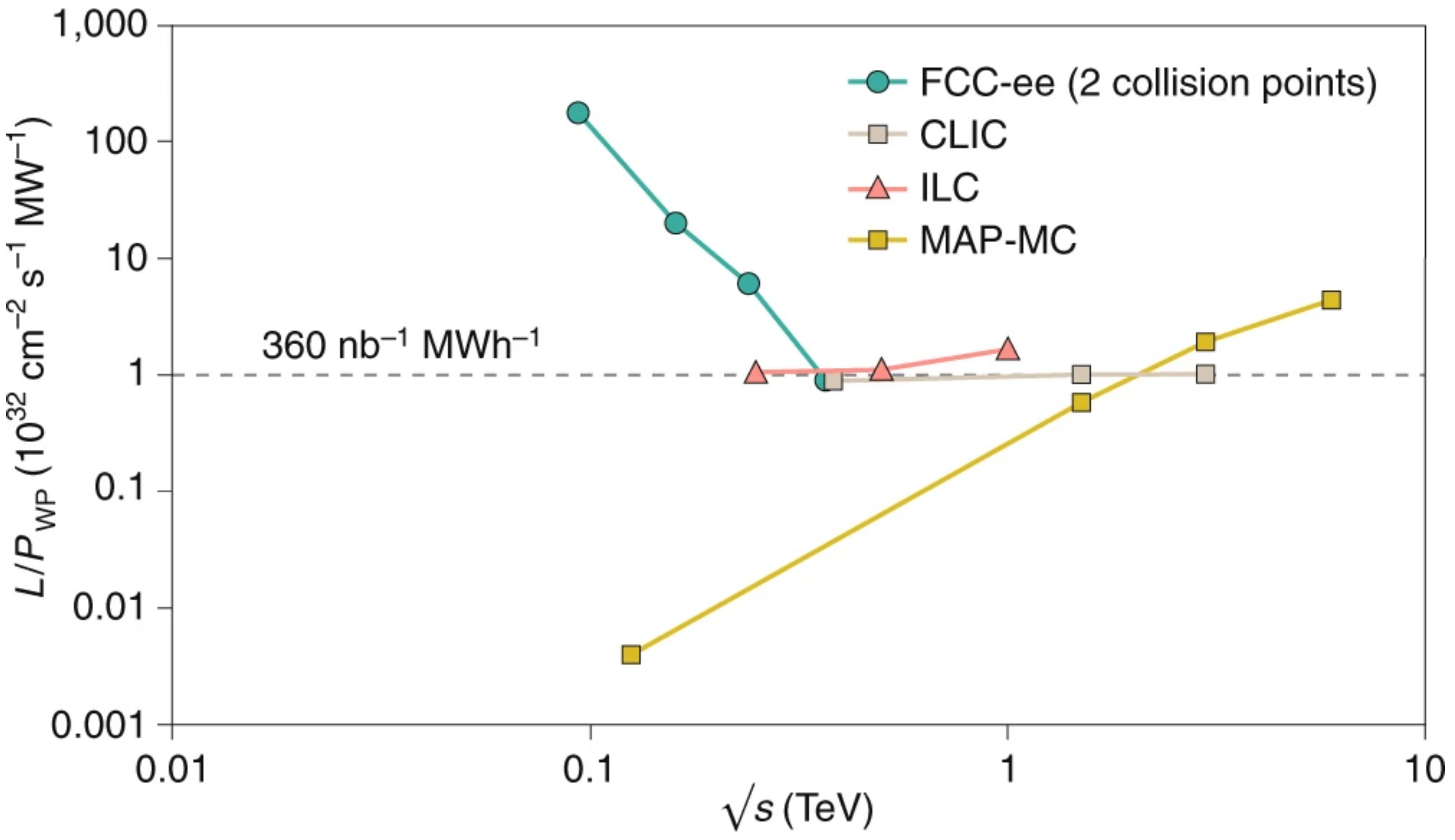
- **Feasibility Study: 2021-2025**
- **If project approved before end of decade, construction can start beginning 2030s**
- **FCC-ee operation ~2045-2060**
- **FCC-hh operation 2070-2090++**

What can we look forward to?

Stage	Collisions	$\sqrt{s}$	Comments
FCC-ee	e+e-	90 GeV (Z) 160 (WW) 240 (H) 365 (tt)	2-4 IP About 15 years of operation Very high luminosity Z pole run (tera-Z)
FCC-hh	pp	100 TeV	2+2 experiments About 25 years of operation
	PbPb	39 TeV	1 run = 1 month of operation
FCC-eh	ep	3.5 TeV	Concurrent operation with pp
	ePb	2.2 TeV	Concurrent operation with PbPb

FCC-ee

Design based on lessons and techniques from past colliders



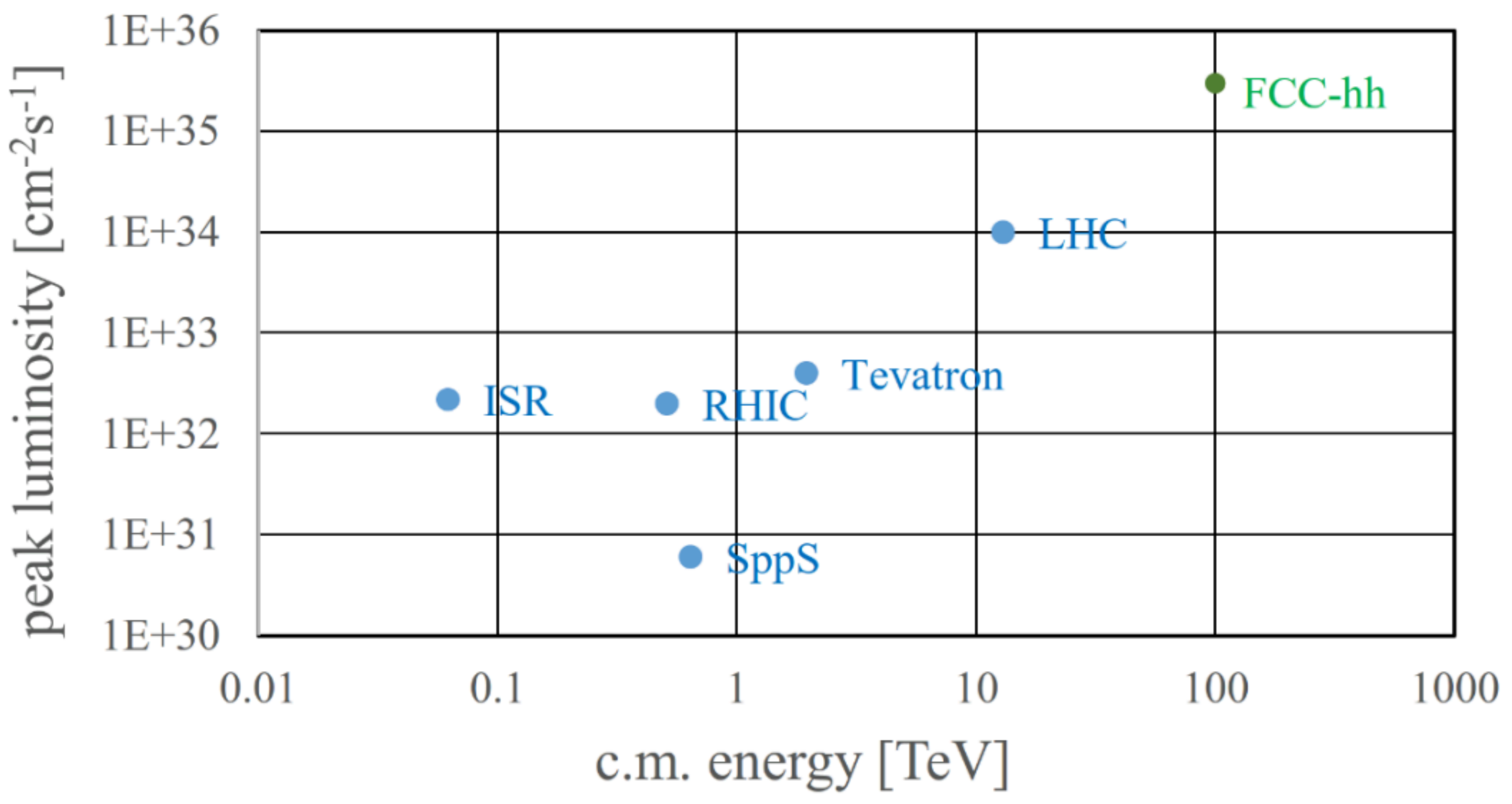
- Great energy range for the heavy particles of the Standard Model
- Complementarity with hadron (LHC, FCC-hh) and linear colliders
- combining successful ingredients of several recent colliders → highest luminosities & energies

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	LEP x 10^5
FCC-ee-W	2	158-162	12	10^8 WW events	LEP x $2 \cdot 10^3$
FCC-ee-H	3	240	5	10^6 ZH events	Never done
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events	Never done

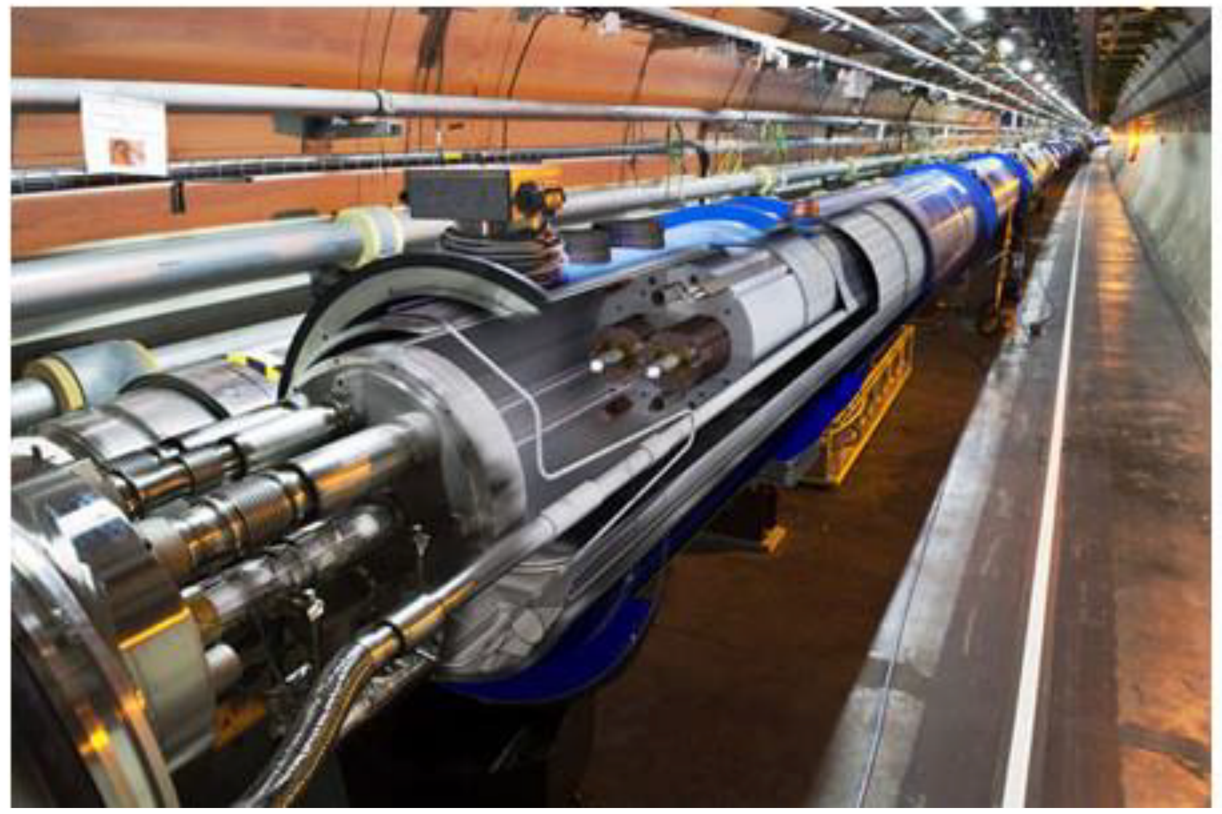
The FCC-ee will be implemented in stages as an electroweak, flavour, and Higgs factory to study with unprecedented precision the Higgs boson, the Z and W bosons, the top quark, and other particles of the Standard Model

FCC-hh

Highest collision energies

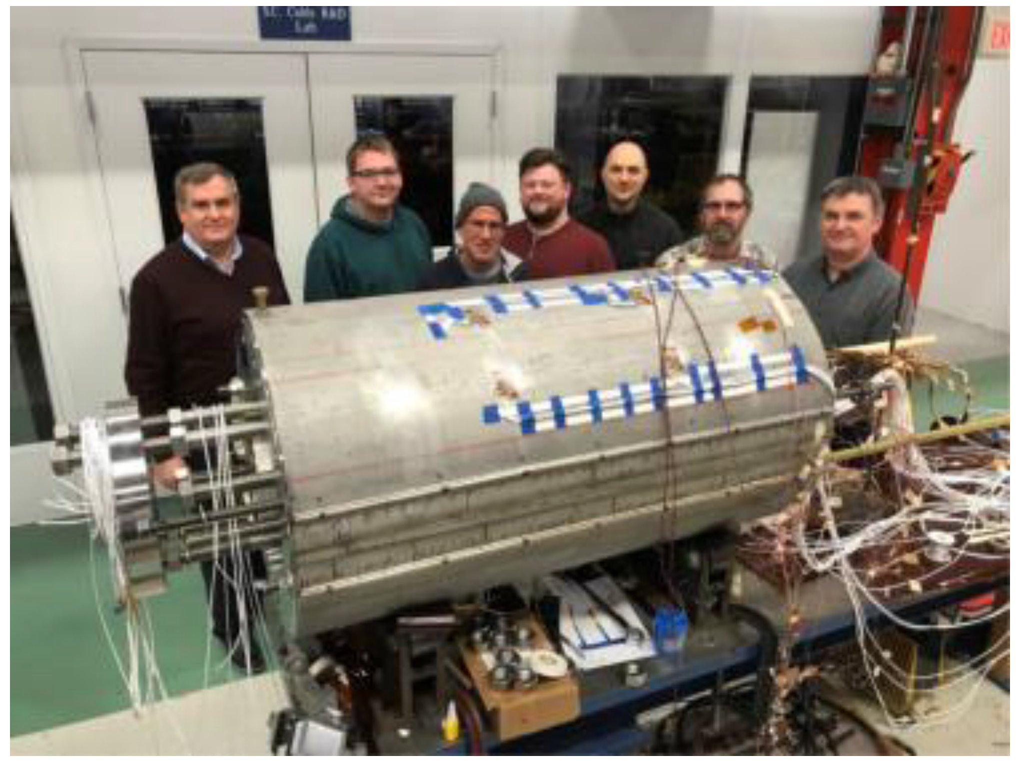


- order of magnitude performance increase in both energy & luminosity wrt the LHC
- 100 TeV collision energy (vs. 14 TeV for LHC)
- 20 ab^{-1} per experiment over 25 years (vs 3 ab^{-1} for LHC)
- Similar increase as from Tevatron to LHC
- Key technology: high-field magnets



from
LHC technology
8.3 T NbTi dipole

via
HL-LHC
technology
12 T NbSn
quadrupole

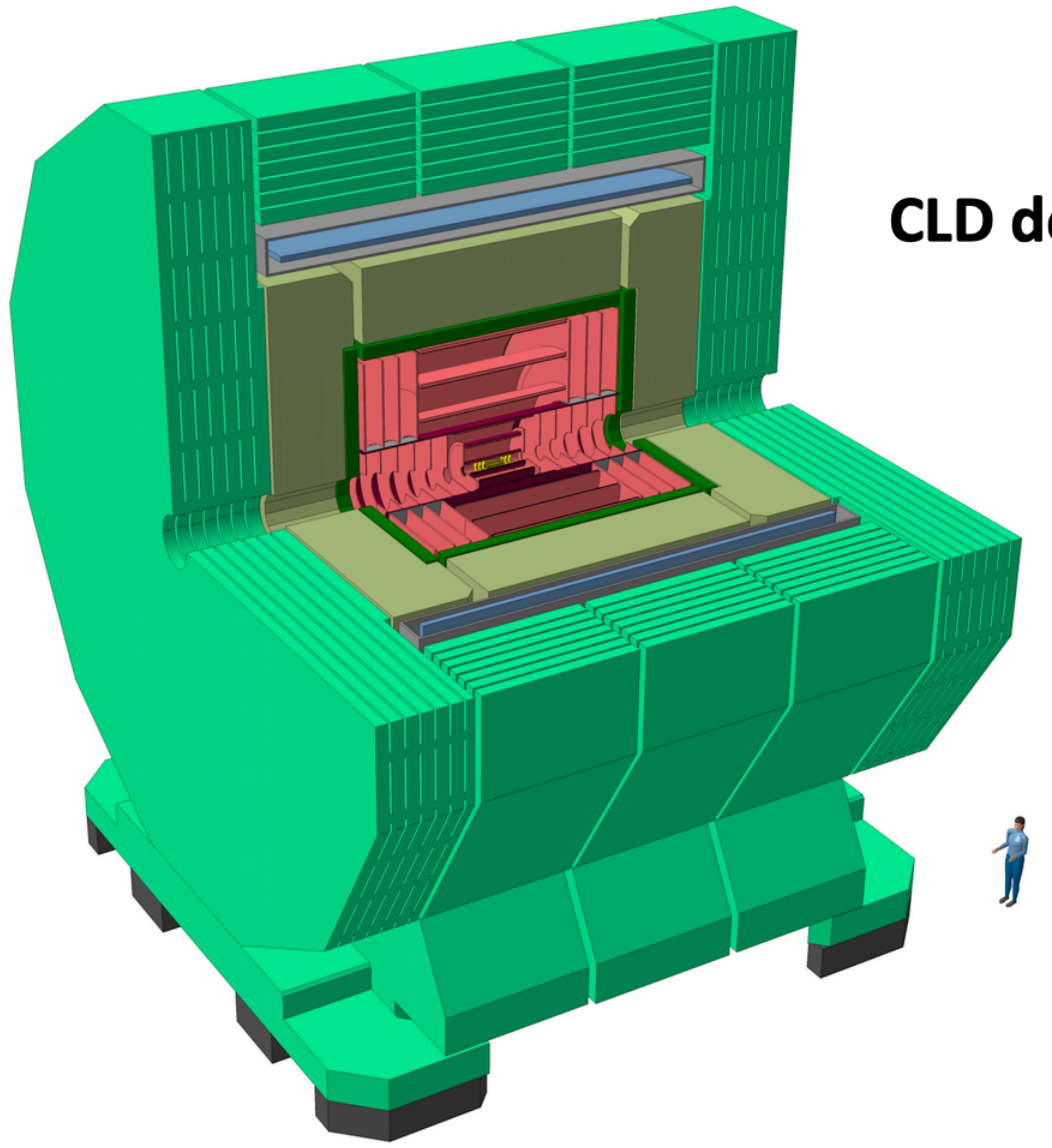


FNAL dipole
demonstrator
14.5 T NbSn

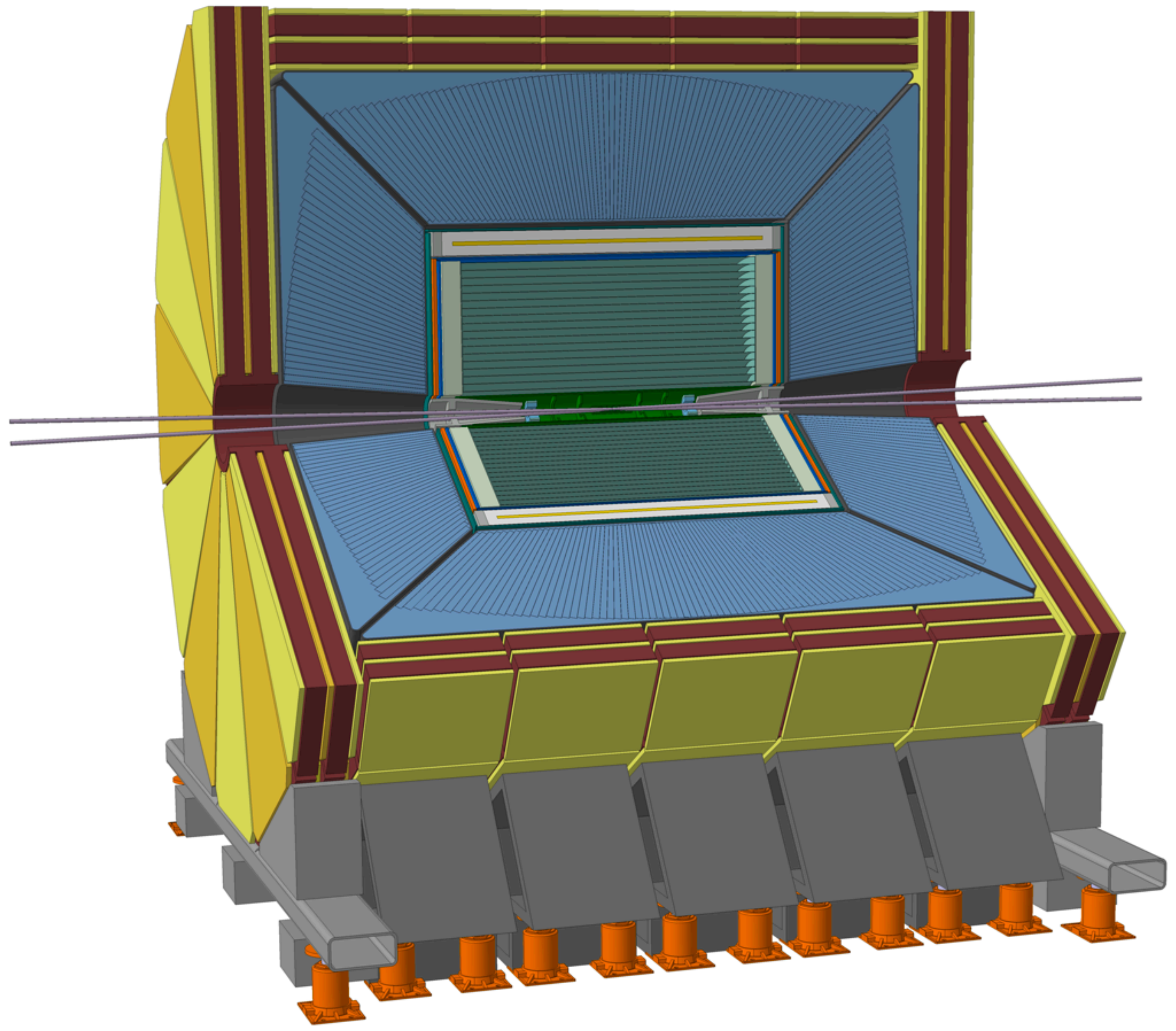
Detector concepts

FCC-ee

- Two concepts used for integration, performance, and cost estimates:
  - One adapted from CLIC: CLD
  - One specifically designed for FCC-ee (and CEPC): IDEA



CLD design

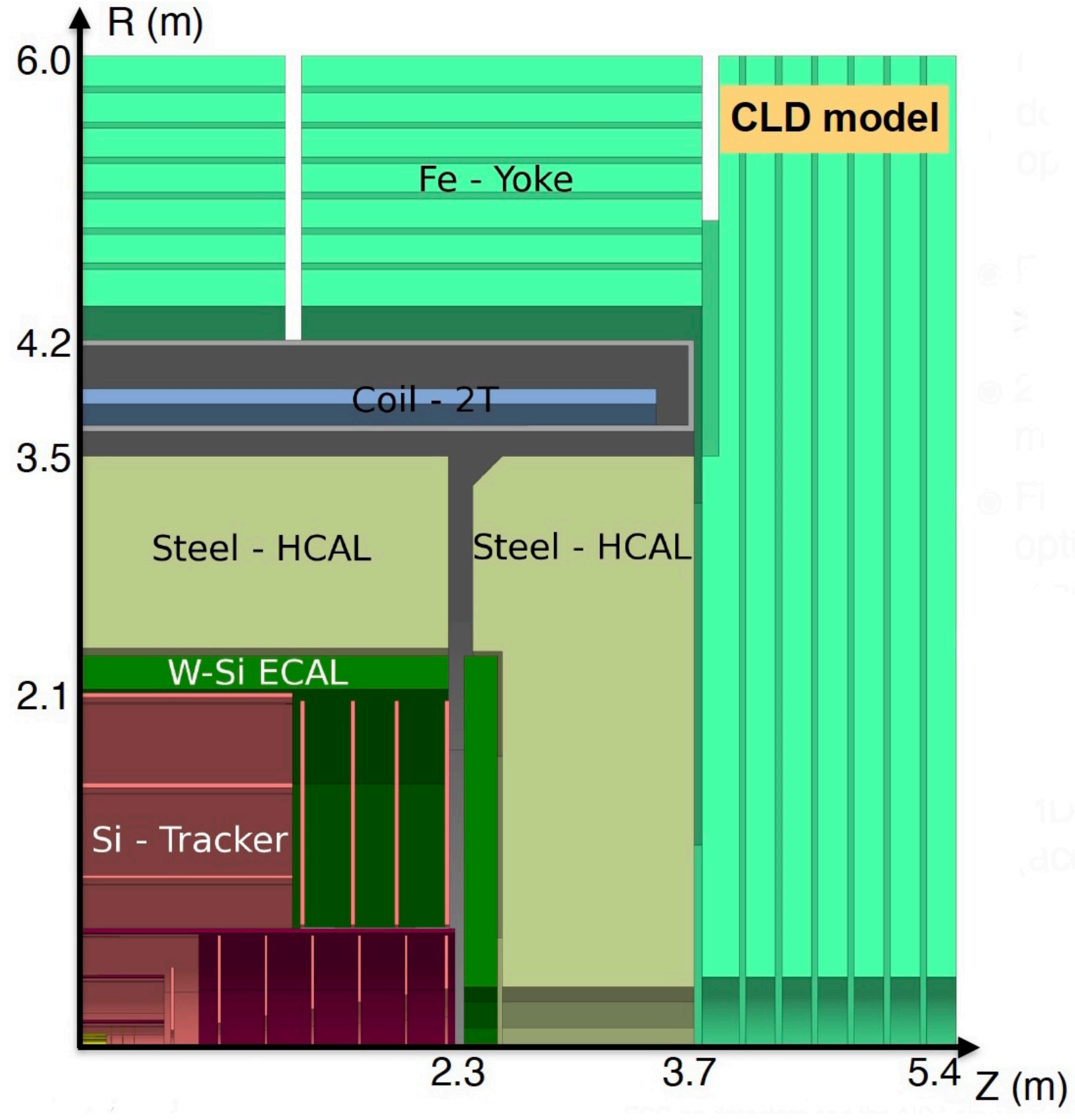


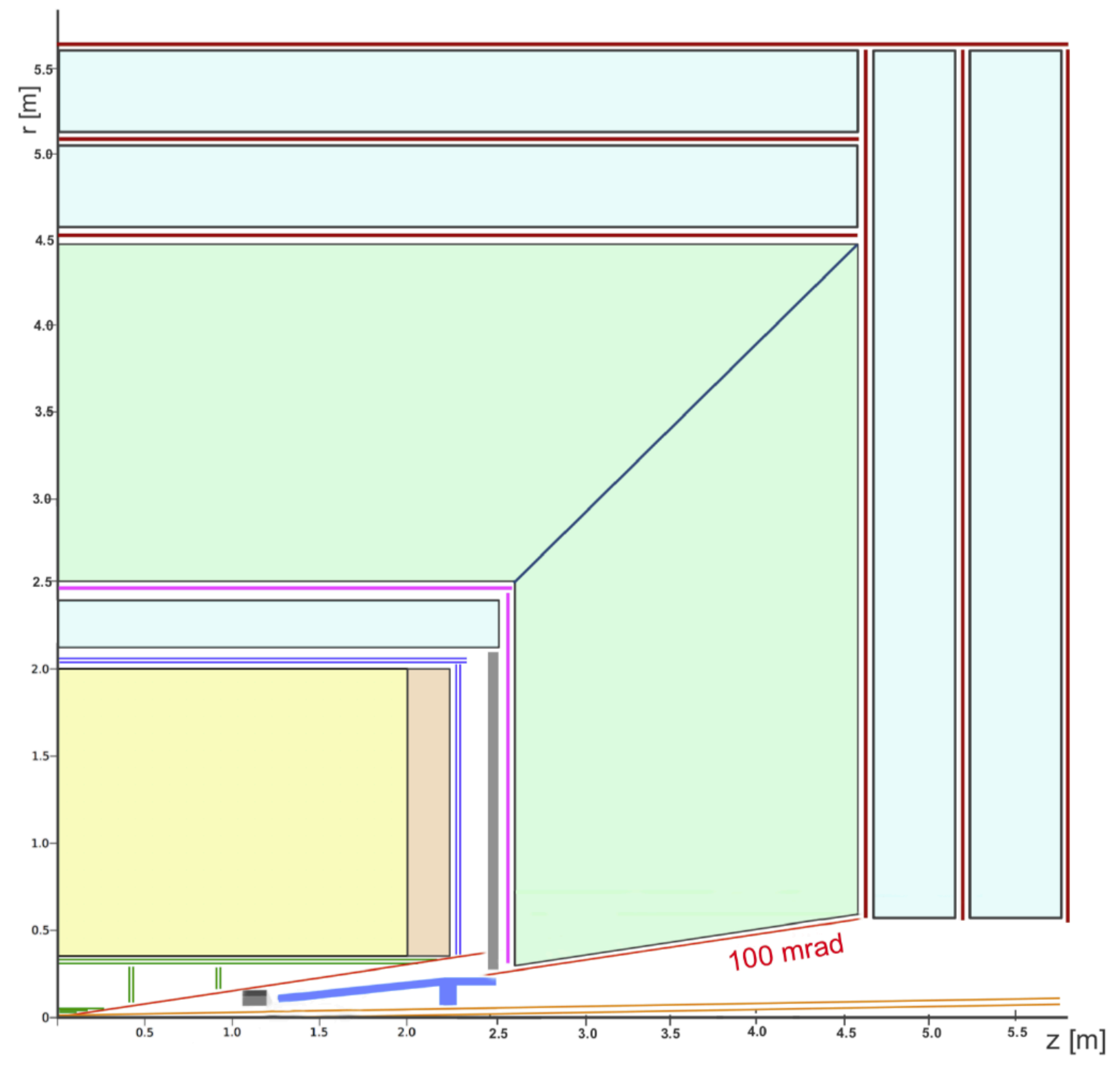
IDEA design

Detector concepts

FCC-ee

- Both about 11 meters long, 6 high
  - CLD: full silicon tracker, 2T magnet field, high granularity ECAL (silicon-tungsten) and HCAL (scintillator-steer), RPCs for muon detectors
  - IDEA: silicon vertex, drift-chambers, dual-readout calorimeter (lead-scintillating, Cherenkov fibres)
- Complementary options possible (especially with 4 experiments)
- Taking a broader look at the physics potential and optimize detector designs for complete physics program: many opportunities to contribute





What about the physics?

- A circular ee + pp collider:
  - indirect high-mass-scale sensitivity + direct search potential
- Best possible precision and sensitivity for
  - Higgs and top properties
  - EWSB phenomena
- Unprecedented exploration potential
  - Direct and indirect

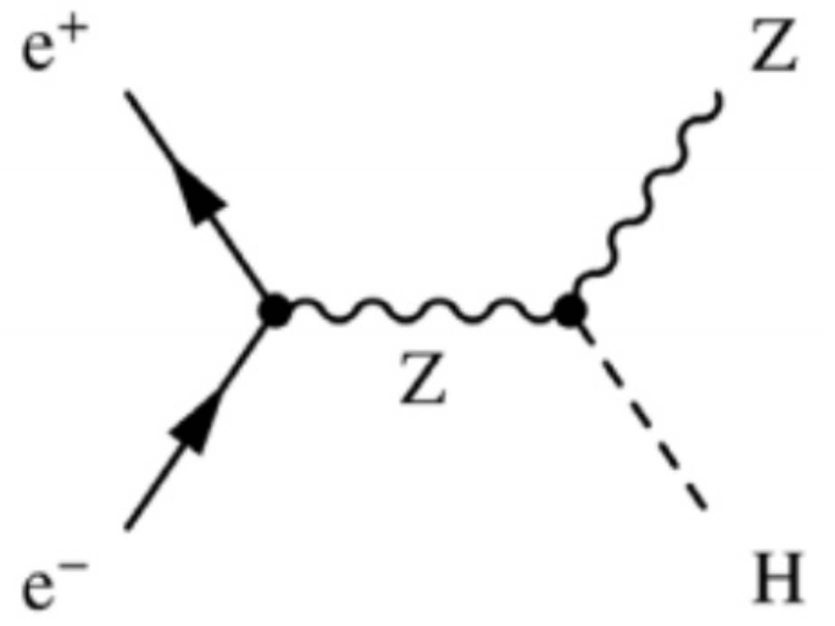
FCC-ee	H	Z	W	t	τ(←Z)	b(←Z)	c(←Z)
	10^6	$5\ 10^{12}$	10^8	10^6	$3\ 10^{11}$	$1.5\ 10^{12}$	10^{12}

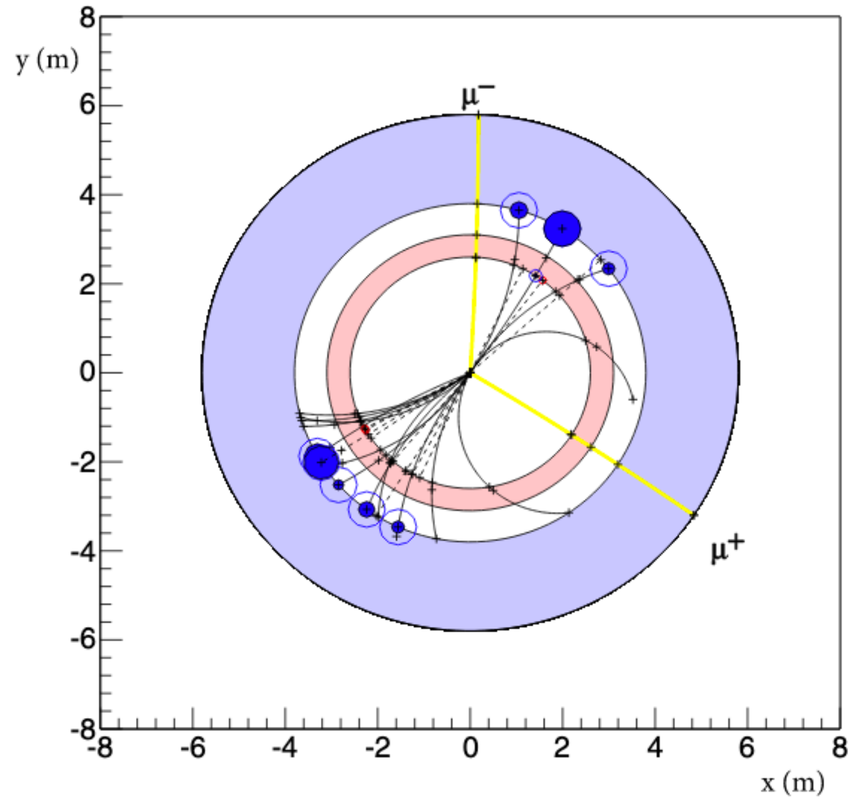
FCC-hh	H	b	t	W(←t)	τ(←W←t)
	$2.5\ 10^{10}$	10^{17}	10^{12}	10^{12}	10^{11}

FCC-eh	H	t
	$2.5\ 10^6$	$2\ 10^7$

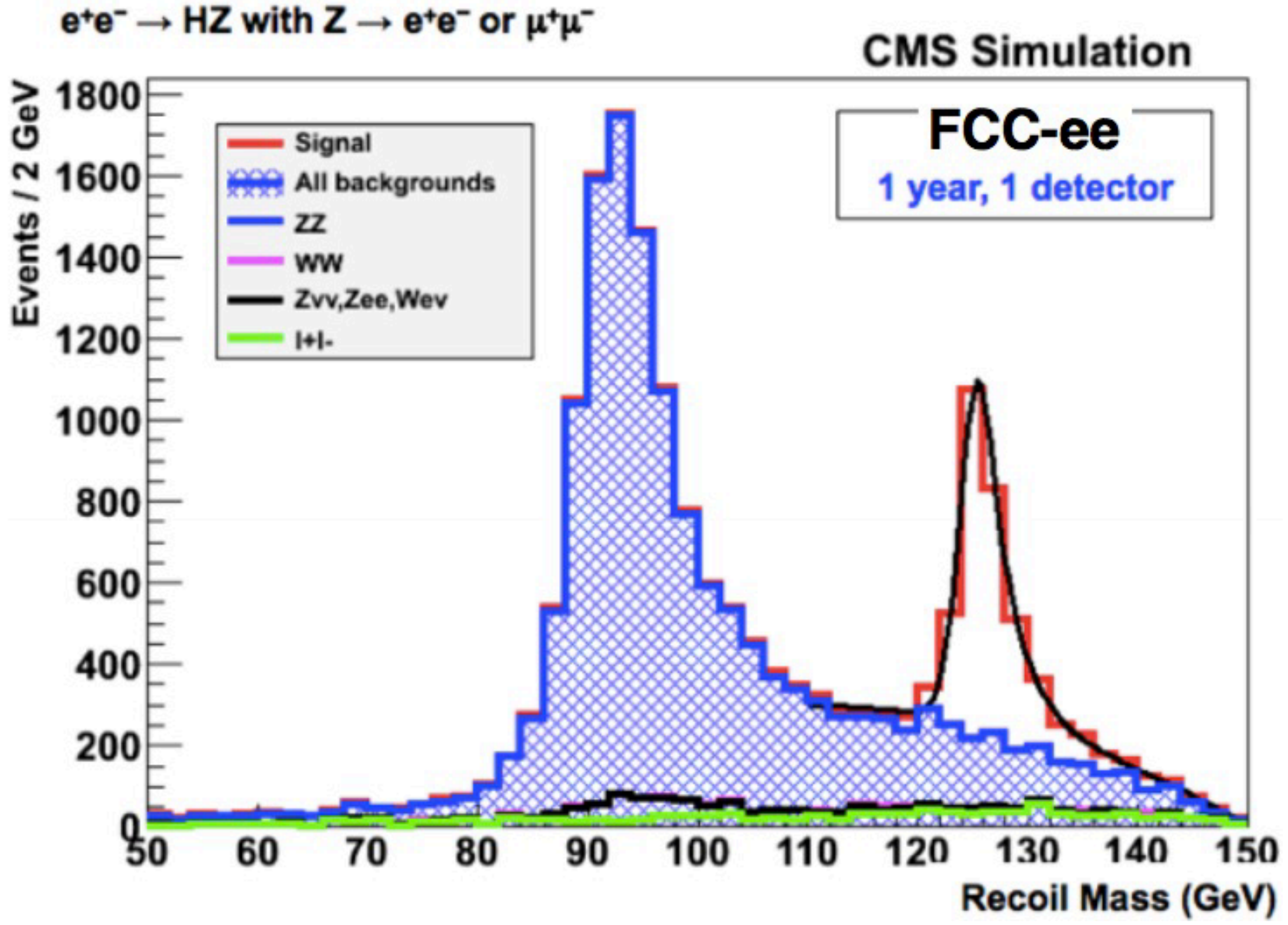
Physics menu

Higgs factory, properties





- Coupling deviations likely to remain unconstrained at HL-LHC
- e+e– →ZH: model independent measurement of HZZ coupling
  - sub-% measurement of couplings to W, Z, b, τ , % to gluon and charm
  - absolute measurement of width and couplings
  - Recoil method: Tag Higgs event independent of decay mode
- pp → H+X: huge statistics + per-mille e+e- measurement of Higgs properties + large dynamic range
  - sub-% measurement of rarer decay modes ≲5% measurement of the trilinear self-coupling
  - probe d > 4 EFT operators up to scales of several TeV
  - search for multi-TeV resonances decaying to H, extensions of the Higgs sector



Precision measurements: couplings, mass, width Searches for Exotic Higgs, invisible decays

Physics menu

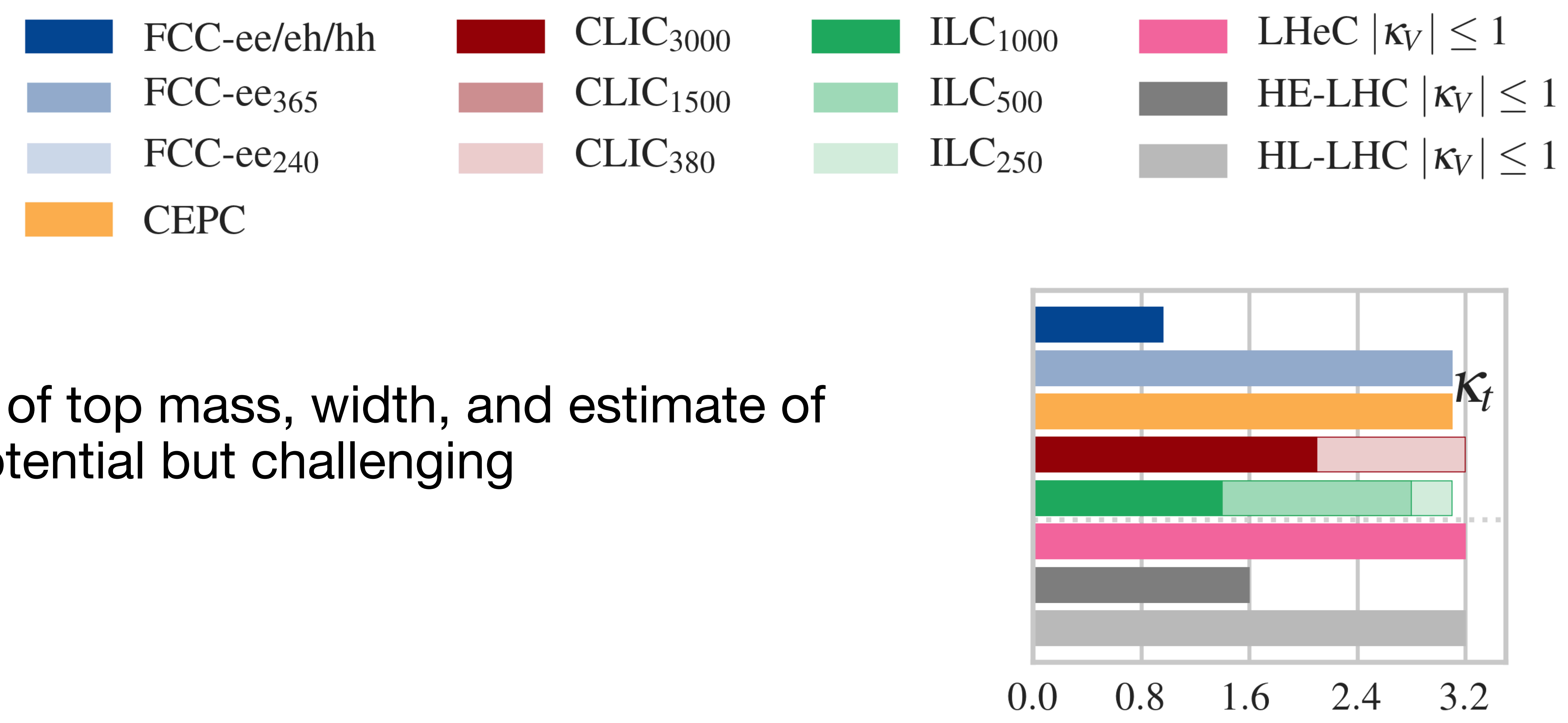
Electroweak observables

- Circular e+e– offers a clear advantage: luminosity
- O(10^5) larger statistics than LEP at the Z peak and WW threshold
- Multiple properties to be measured to unprecedented precision: masses, asymmetries, branching ratios, widths…

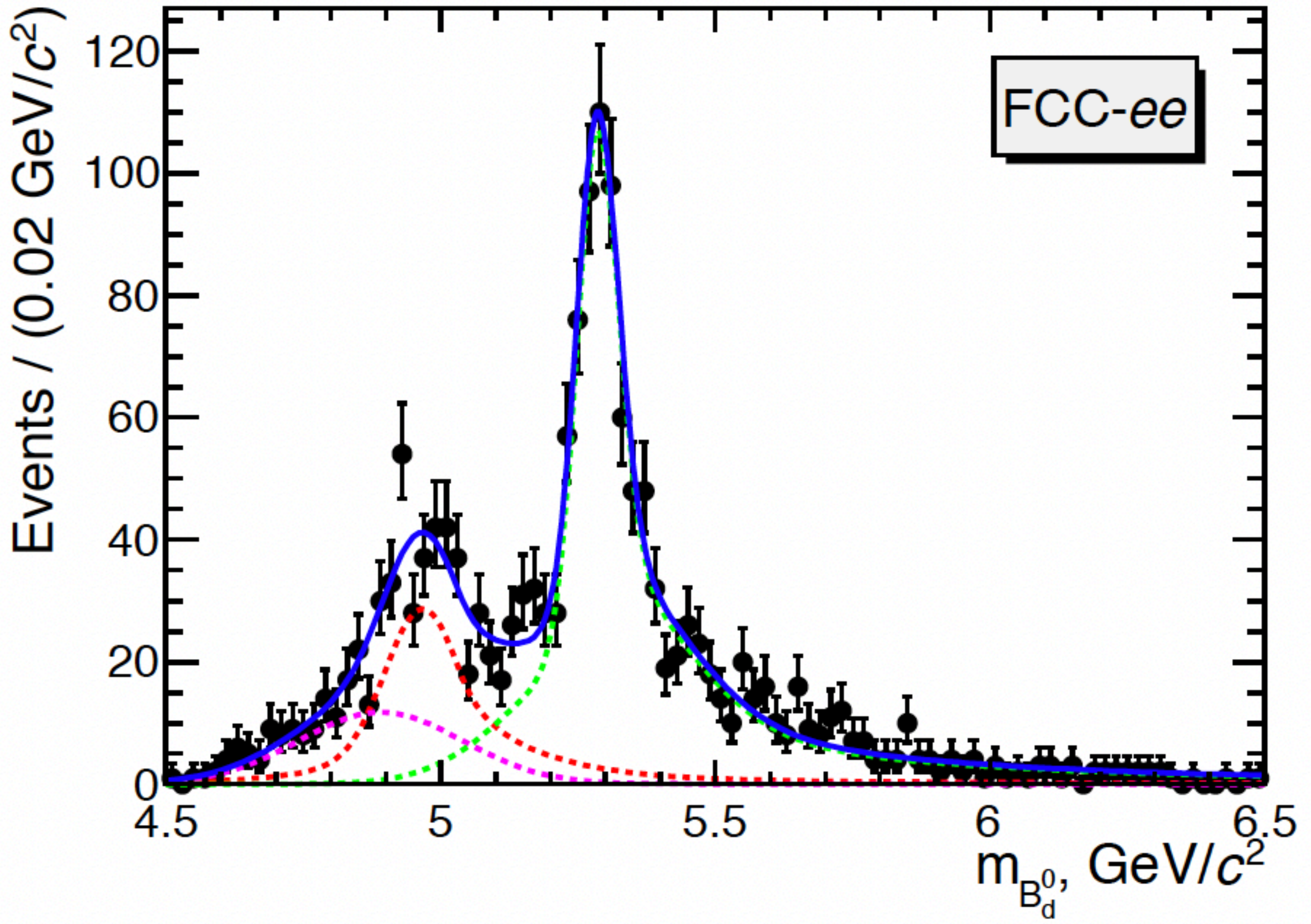
Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91{,}186{,}700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	$2{,}495{,}200 \pm 2300$	8	100	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20{,}767 \pm 25$	0.06	0.2–1.0	Ratio of hadrons to leptons acceptance for leptons
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6	From R_ℓ^Z above [43]
R_b ($\times 10^6$)	$216{,}290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [44]
σ^0_{had} ($\times 10^3$) (nb)	$41{,}541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	$231{,}480 \pm 160$	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}$ (m_Z) ($\times 10^3$)	$128{,}952 \pm 14$	4	Small	From $A_{FB}^{\mu\mu}$ off peak [34]
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics
m_W (MeV)	$80{,}350 \pm 15$	0.5	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small	From R_ℓ^W [45]
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	$172{,}740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{CM} = 365$ GeV run

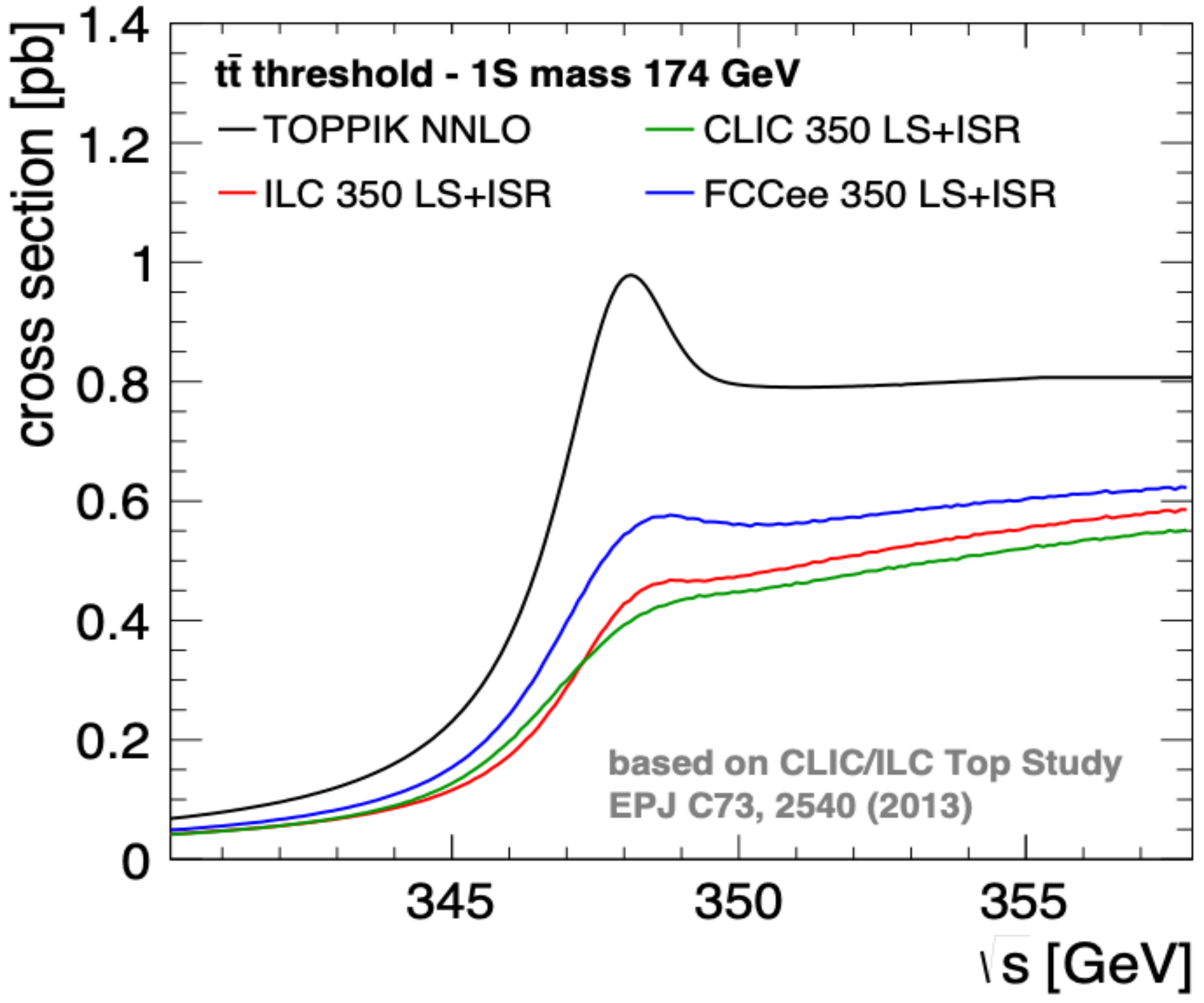
Physics menu

Top and flavor



- Threshold region allows most precise measurements of top mass, width, and estimate of Yukawa coupling at FCC-ee, at FCC-hh incredible potential but challenging reconstruction
- Tera-Z run of the FCC-ee 15x Belle's stats
  - Great potential for studies of flavor anomalies
  - Large tau production, boost
  - All b-hadron species available, potential for excellent secondary vertex reconstruction
  - Experiments at FCC-ee can cover the full program of LHCb & Belle II and compete favorably everywhere

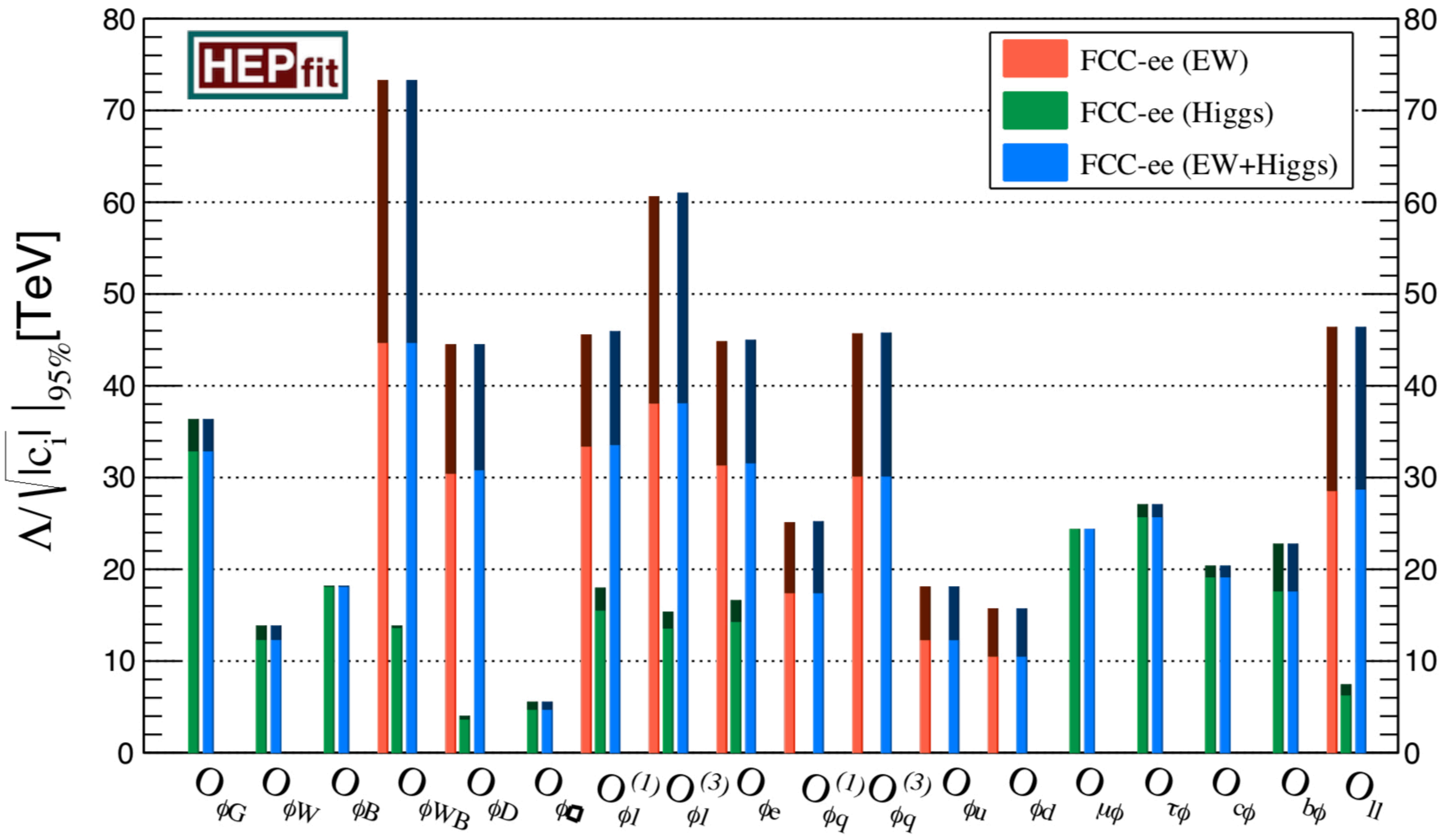




Physics menu

Precision measurements towards discovery

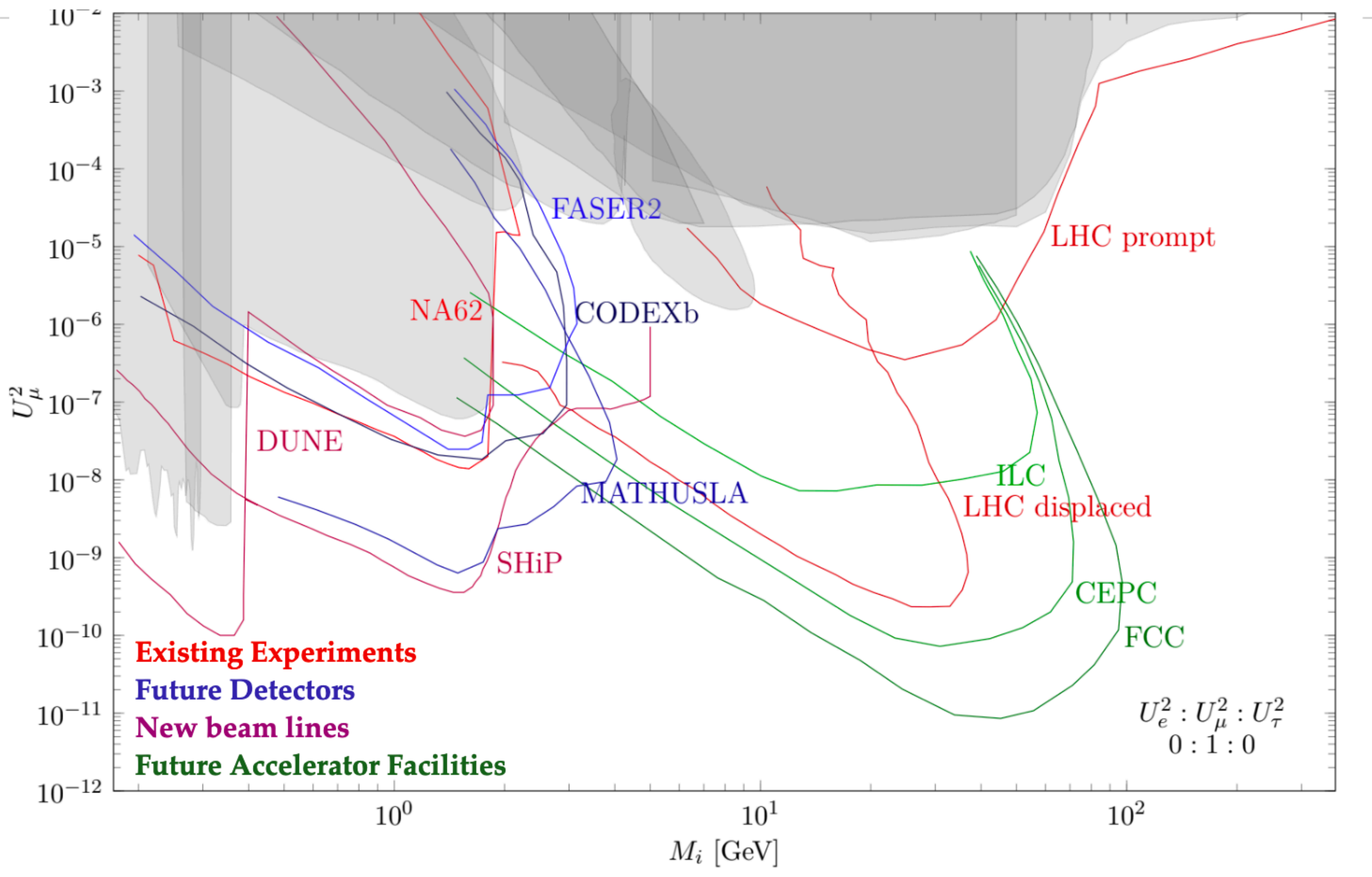
- Complementary Global EFT fits to EW and Higgs observables at FCC-ee
    - Deviating operators may point to new physics to be found by the FCC-hh
- 100 TeV is the appropriate energy to directly search for new physics appearing indirectly through precision EW and H measurements at the FCC-ee



Physics menu

Direct searches for new phenomena

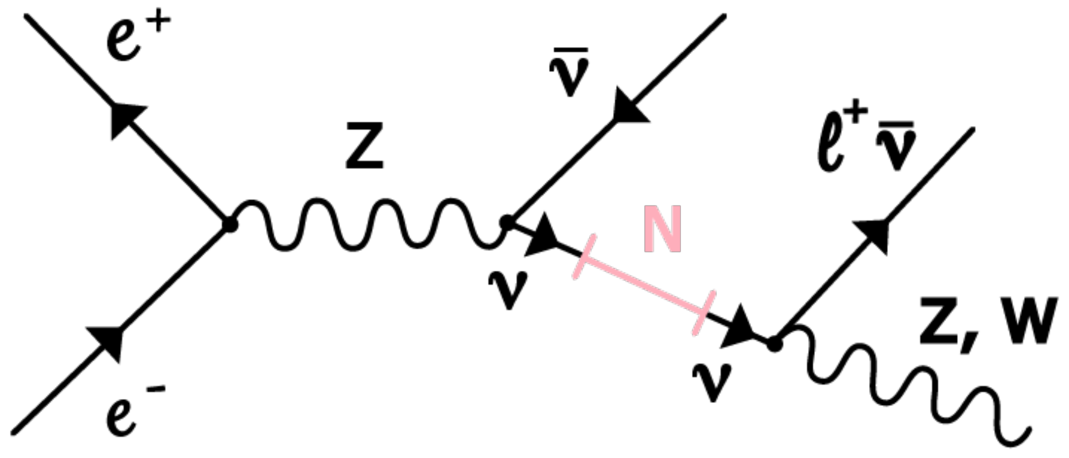
- Direct search at high scales will be the business of the FCC-hh
    - Pushing the energy frontier!
- All stages also offer potential for direct searches of new, feebly interacting particles that could manifest long-lived signatures
    - closely linked to dark matter, neutrino masses, or to the Baryon Asymmetry of the Universe (or the three of them!)
        - ALPs, exotic Higgs decays, Heavy Neutral Leptons



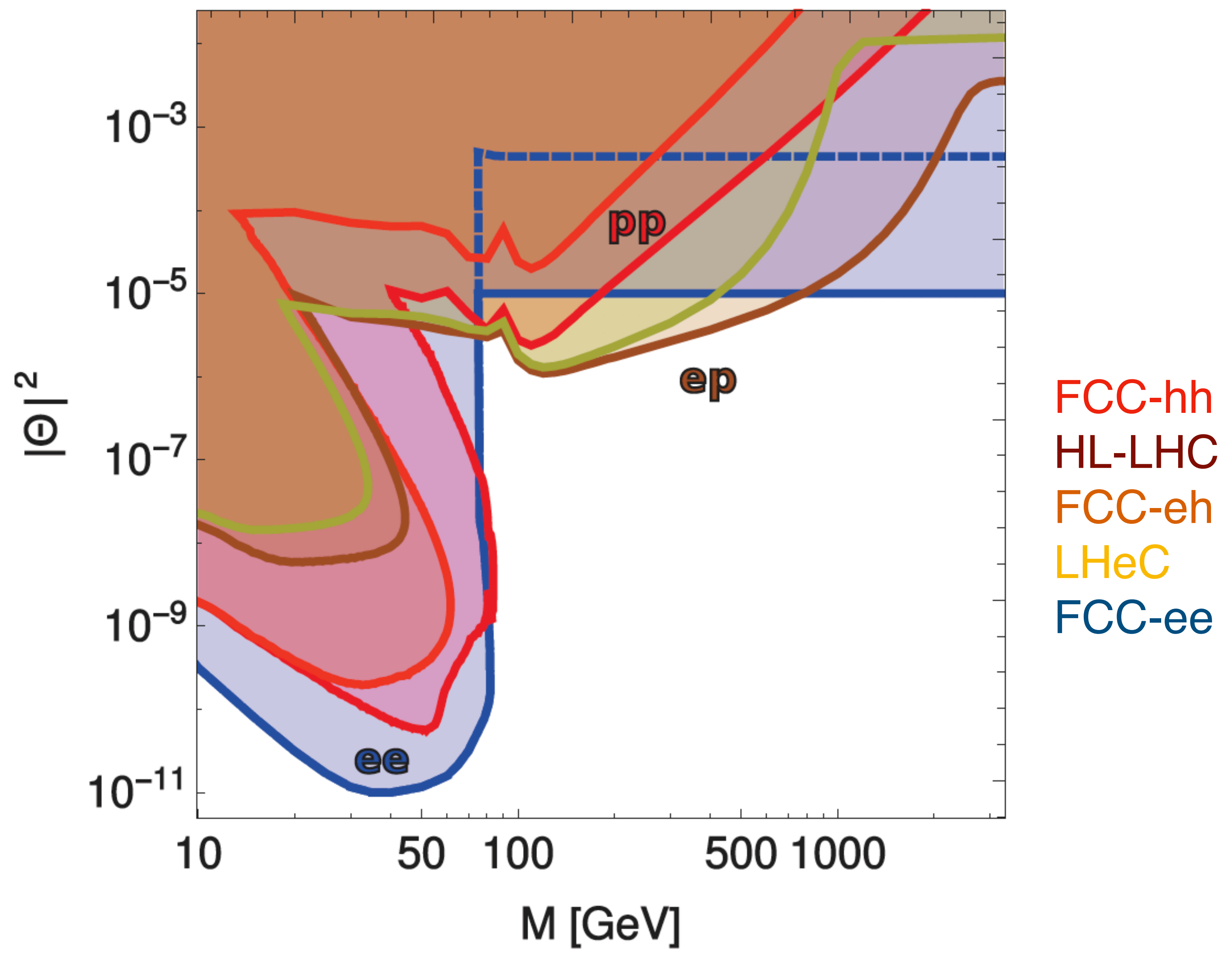
Marco Drewes (FCC-ee LLP informal team)

Complementarity

FCC-ee/-hh/-eh



arXiv:1612.02728



FCC-ee

Indirect constrains from precision SM measurements

Direct search: single HNL production in Z decays

Sensitive to 10^{-11} for M below the W mass

FCC-hh

Direct search: single HNL production in W/Z decays

Lepton Number Violation, Lepton Flavor Violation

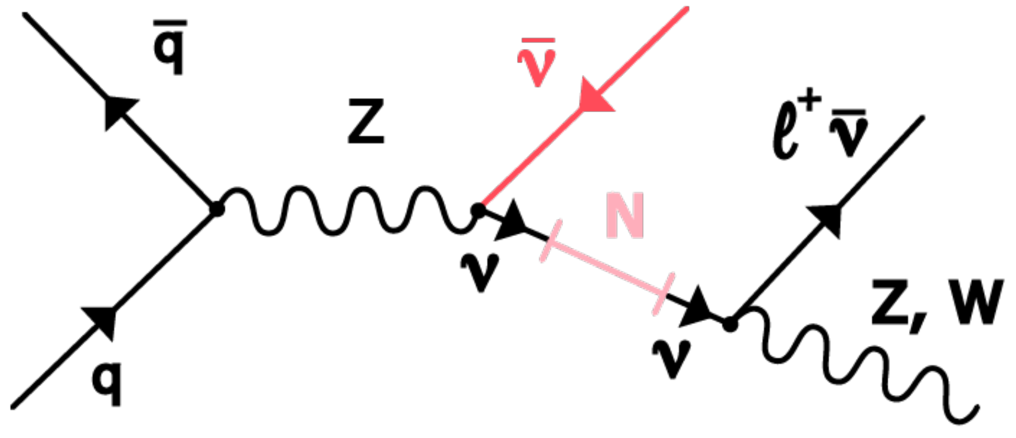
can test heavy neutrinos with masses up to ~2 TeV

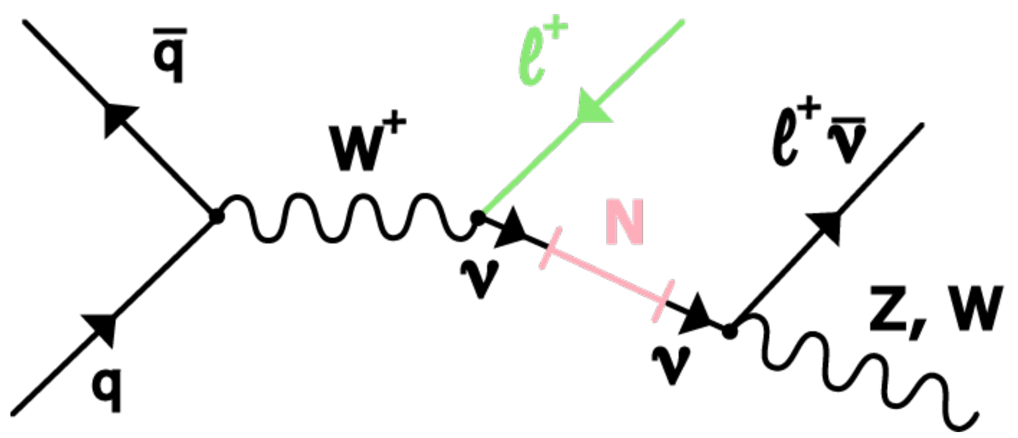
FCC-eh

Can extend the reach of the FCC-hh up to ~2.7 TeV

Best reach above W mass

Sensitive to LFV and Lepton-Number-violation signatures





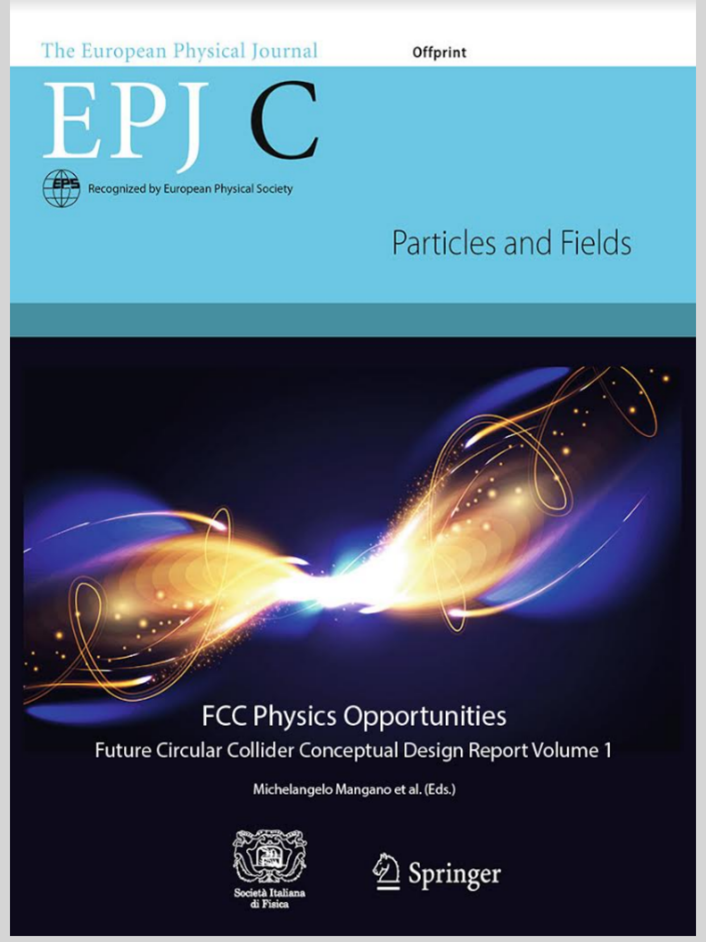
Complementarity is the key word, also in Higgs physics, top physics, and multiple new physics searches

Find out more

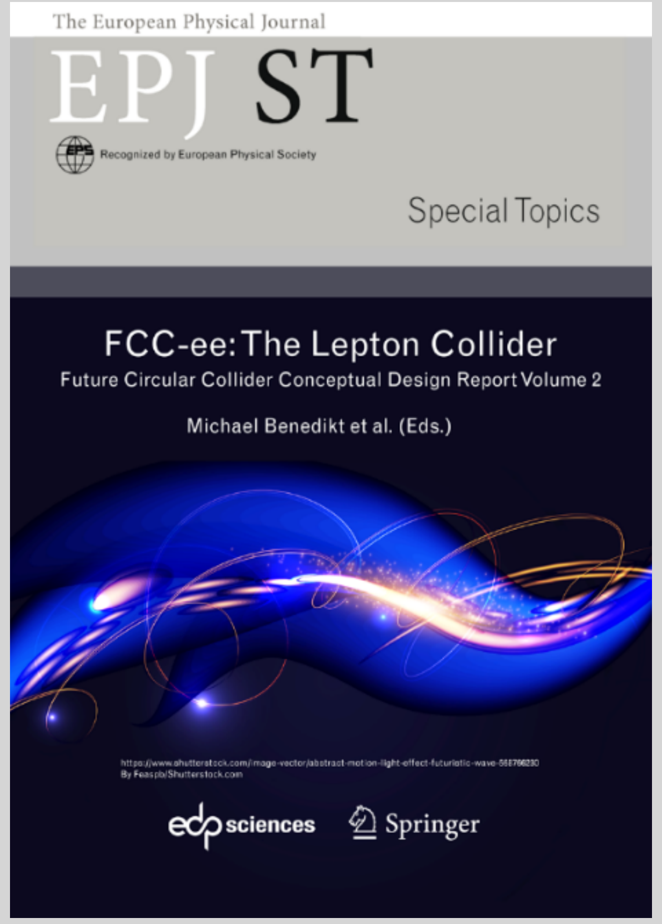
FCC documentation

- Future Circular Collider - European Strategy Update Documents: (FCC-ee), (FCC-hh), (FCC-int)
- FCC-ee: Your Questions Answered: arXiv:1906.02693
- Circular and Linear e+e- Colliders: Another Story of Complementarity: arXiv:1912.11871
- Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders: arXiv:1901.02648
- Polarization and Centre-of-mass Energy Calibration at FCC-ee: arXiv:1909.12245
- FCC-ee Snowmass2021 LoIs: https://indico.cern.ch/event/951830/
- Focus Point on A Future Higgs & Electroweak Factory (FCC): Challenges towards Discovery - Part II: Physics Opportunities and Challenges
  - https://link.springer.com/journal/13360/topicalCollection/AC_e20d0ca1d36bc88d0e8c796d3f2e083a

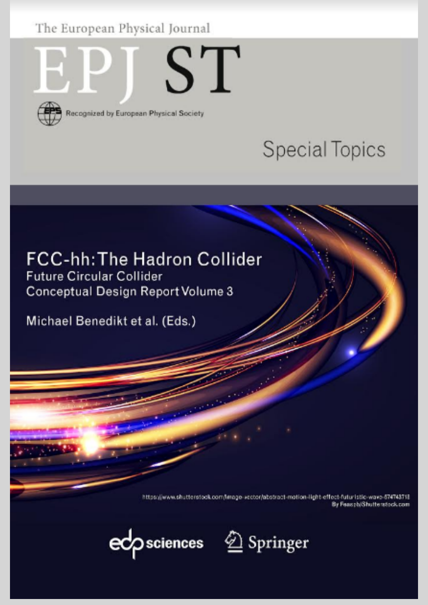
4 CDR volumes published in EPJ



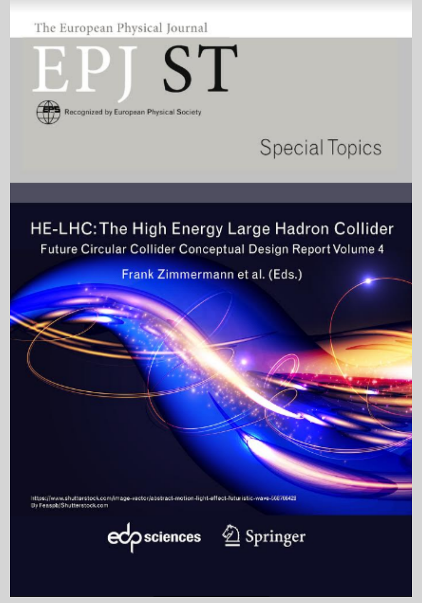
FCC Physics Opportunities



FCC-ee: The Lepton Collider



FCC-hh: The Hadron Collider

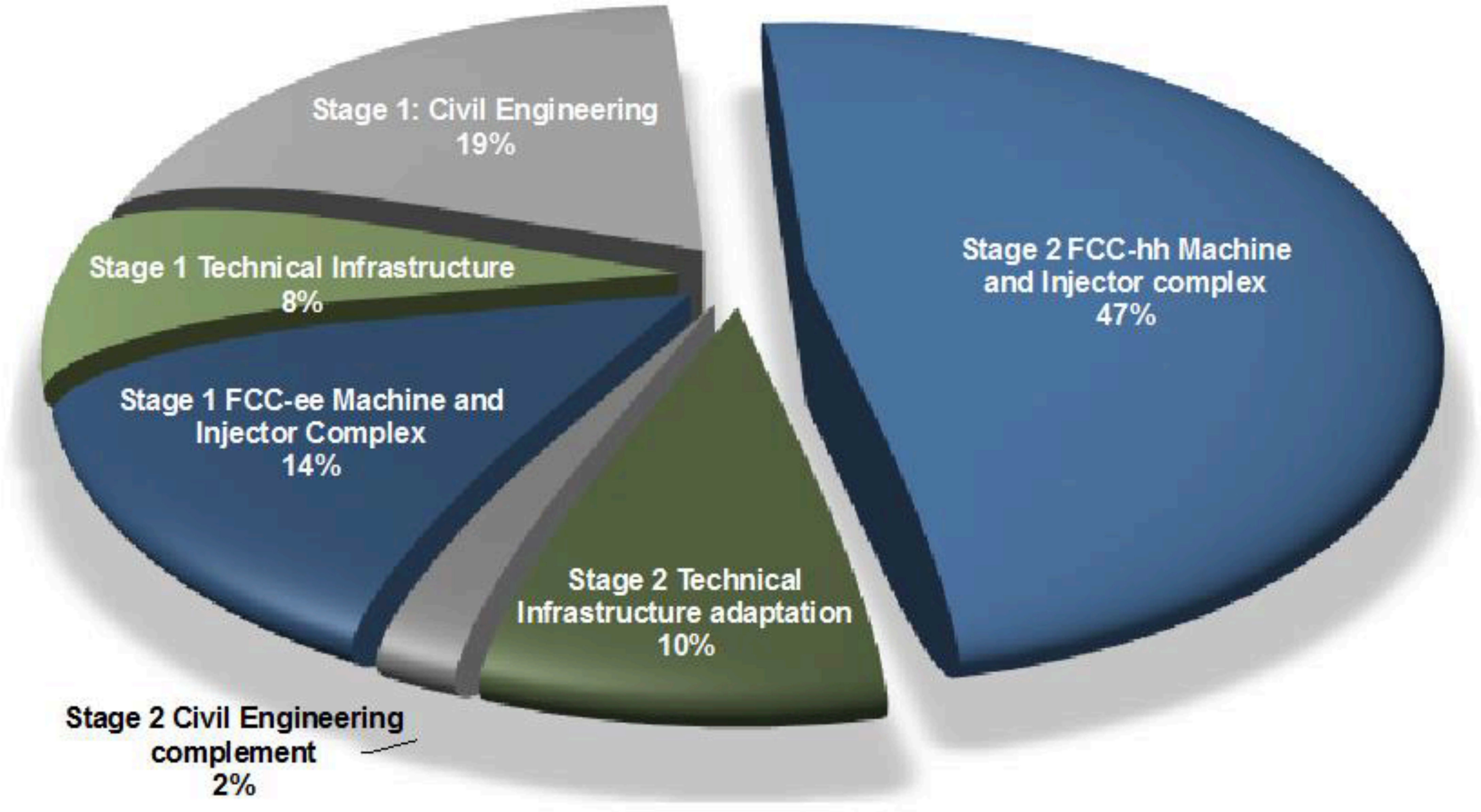


HE-LHC: The High Energy Large Hadron Collider

Backup

How much will all of this cost?

Domain	MCHF
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	28,600



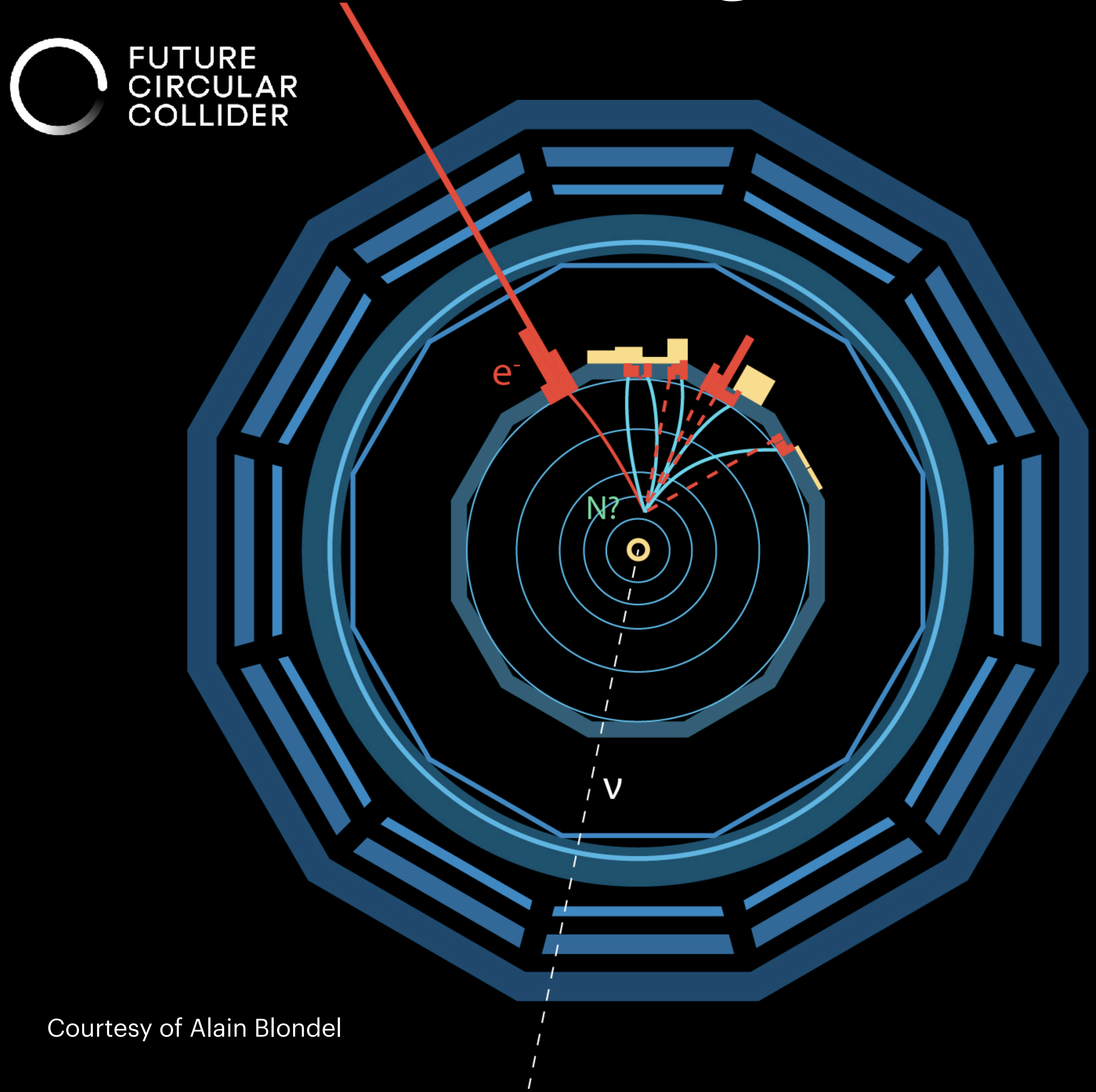
Total construction cost FCC-ee (Z,W,H) ~ 10.5 BCHF + 1.1 BCHF (tt)
Associated to a total project duration of ~20 years

Total construction cost for subsequent FCC-hh ~17 BCHF
Associated to a total project duration of ~25 years

70+ years from feasibility study to decommissioning

(FCC-hh standalone would cost 25BCHF, so not building FCC-ee in a first stage would be a marginal saving)

FCC-ee: Long-lived Heavy Neutral Leptons



Courtesy of Alain Blondel

- Many of the current limits cover high neutrino mixing values
- For low values of the neutrino mixing angle, the decay length of the heavy neutrino can be significant
  - Long-lived signatures
  - Z → νN, N → lW
    - displaced vertex search