Heavy neutrino searches at the FCC

XIX International Workshop on Neutrino Telescopes
18-26 February 2021

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Funded by The Swedish Research Council VR 2017-05092

The European Strategy for Particle Physics

2020 Update

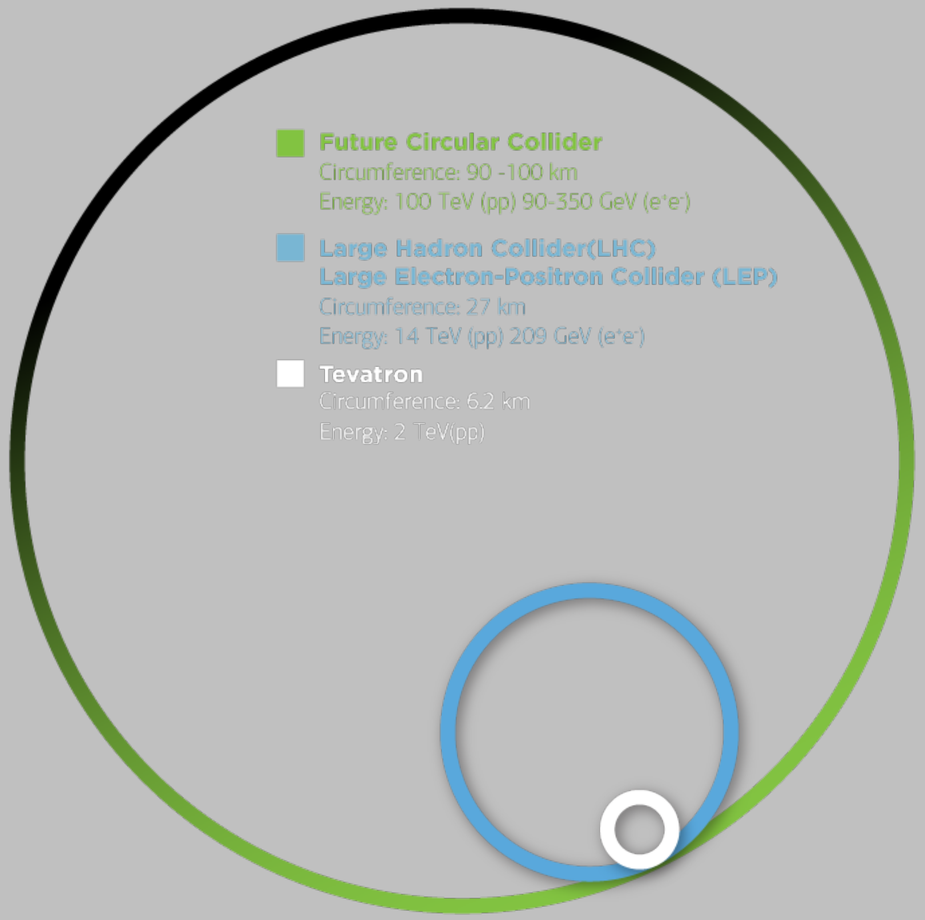
- “An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. […]”

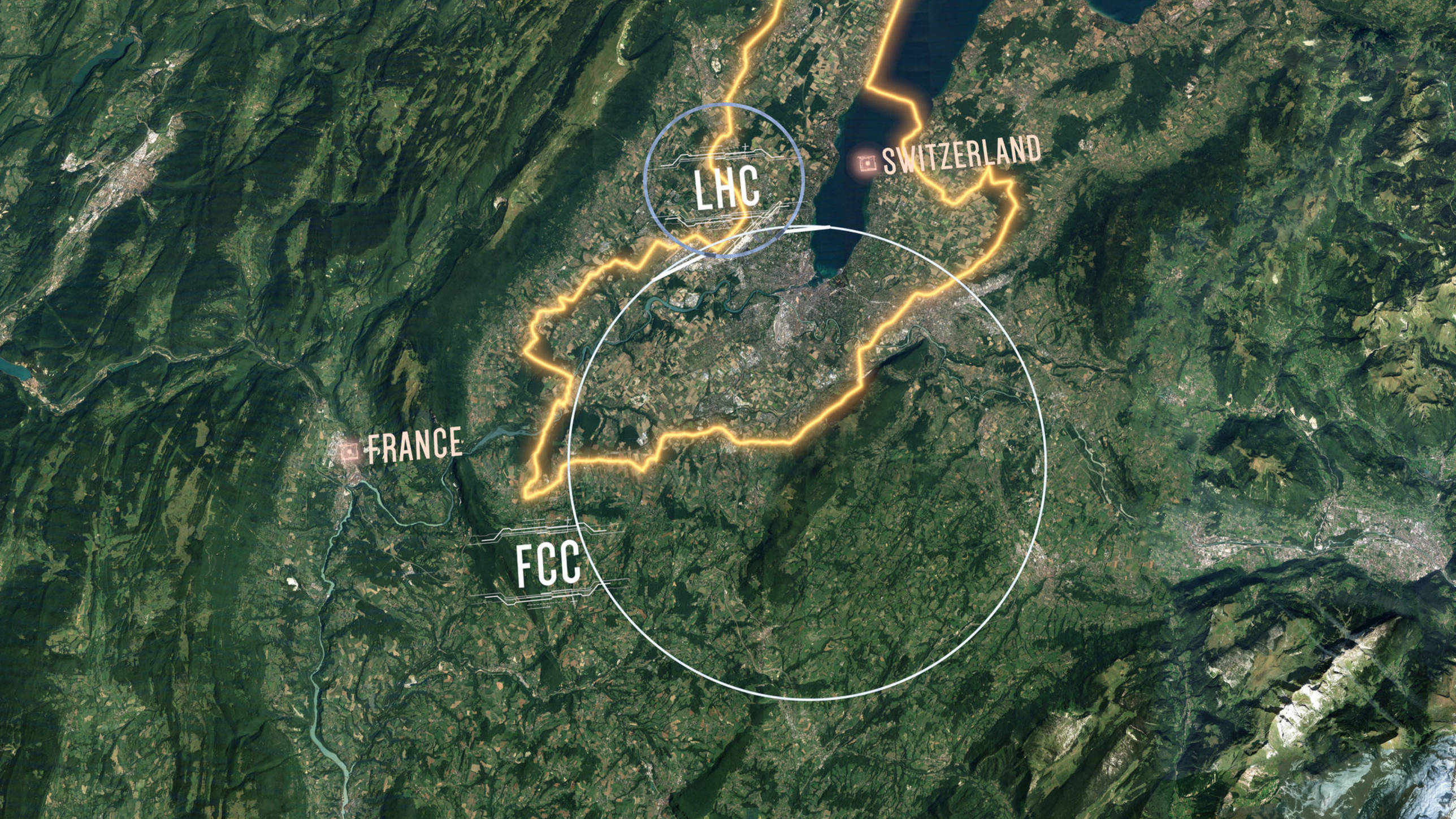
- “Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavor […]”

What is the FCC?

The Future Circular Collider (FCC) integrated program

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

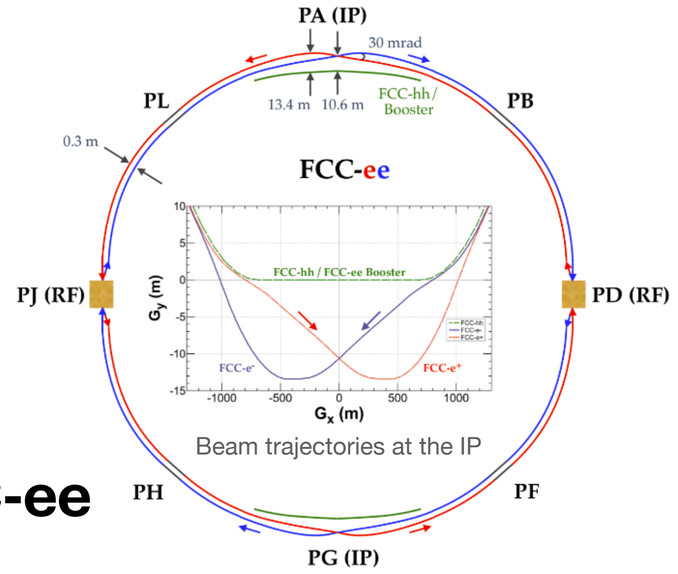



LHC
SWITZERLAND
FRANCE
FCC

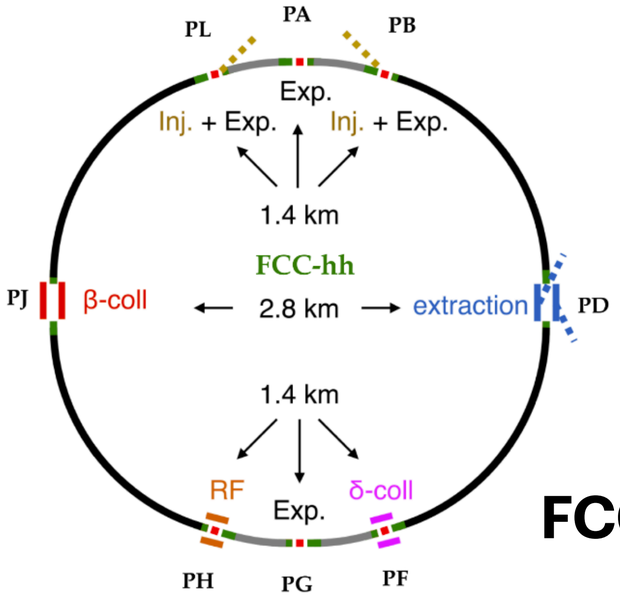
Complementarity: infrastructure

FCC-ee/-hh

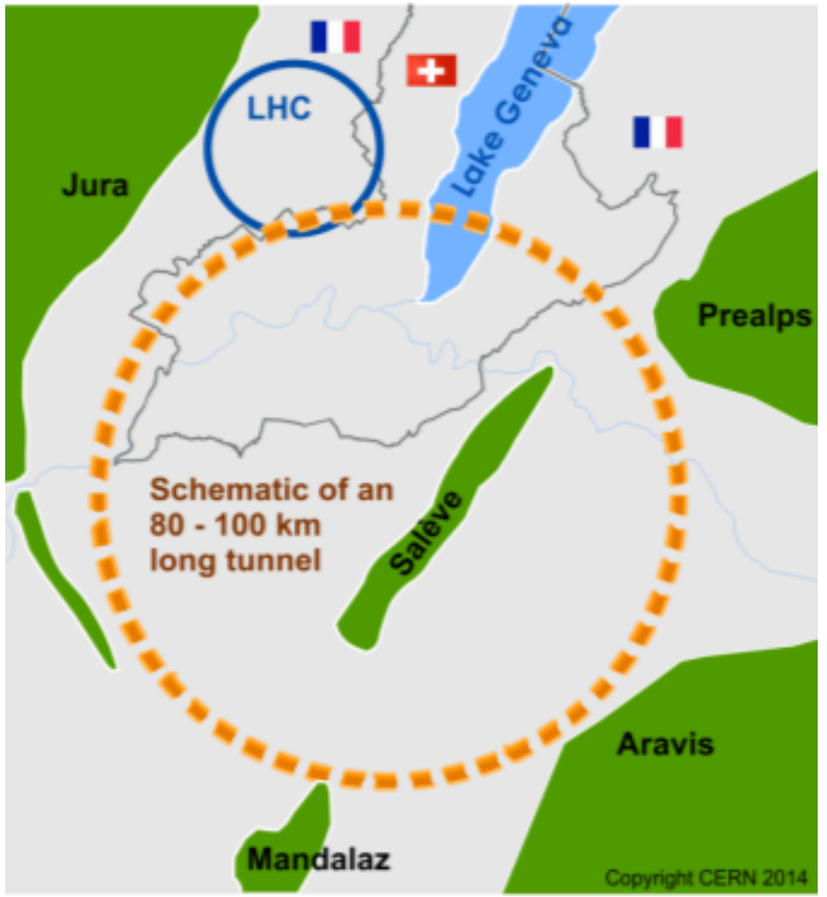
- Sequential implementation maximizes the physics reach at the precision and the energy frontiers
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure
- The FCC-ee booster footprint coincides with that of the FCC-hh



FCC-ee



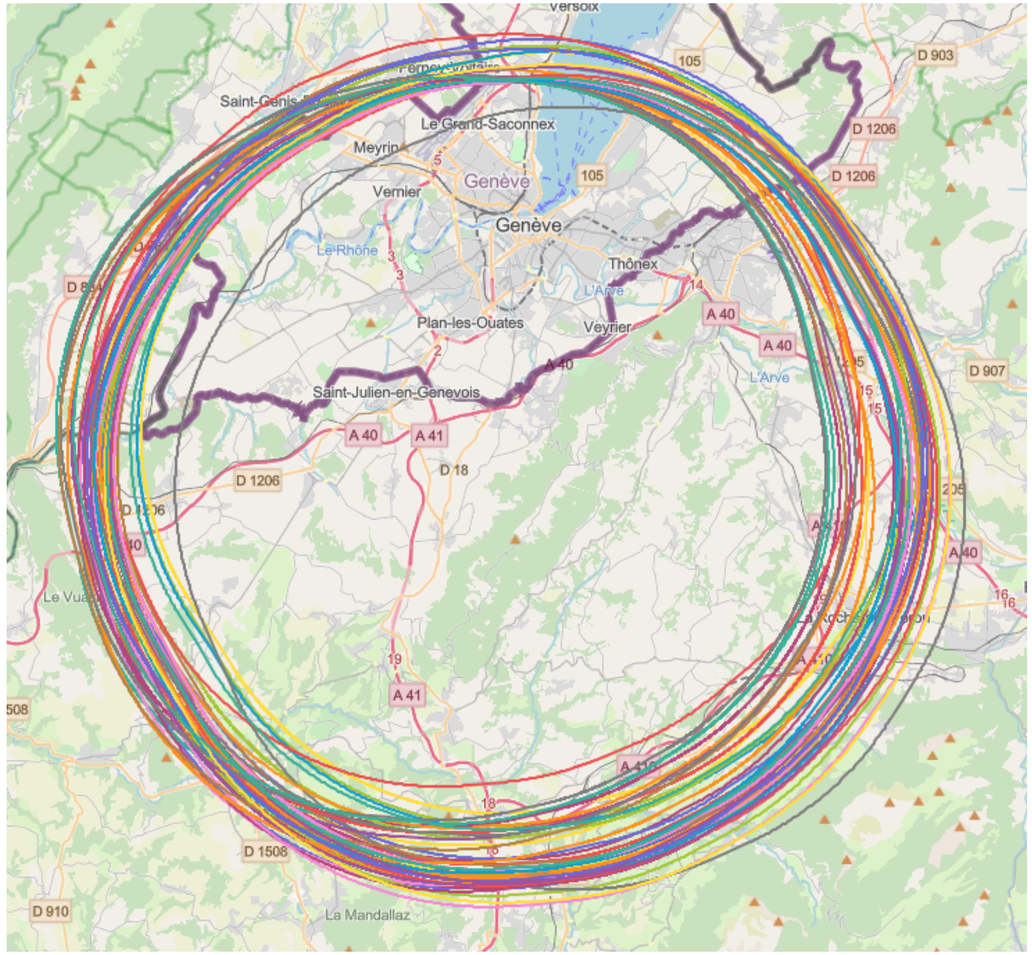
FCC-hh



Collider placement optimisation

Following European and local regulatory frameworks

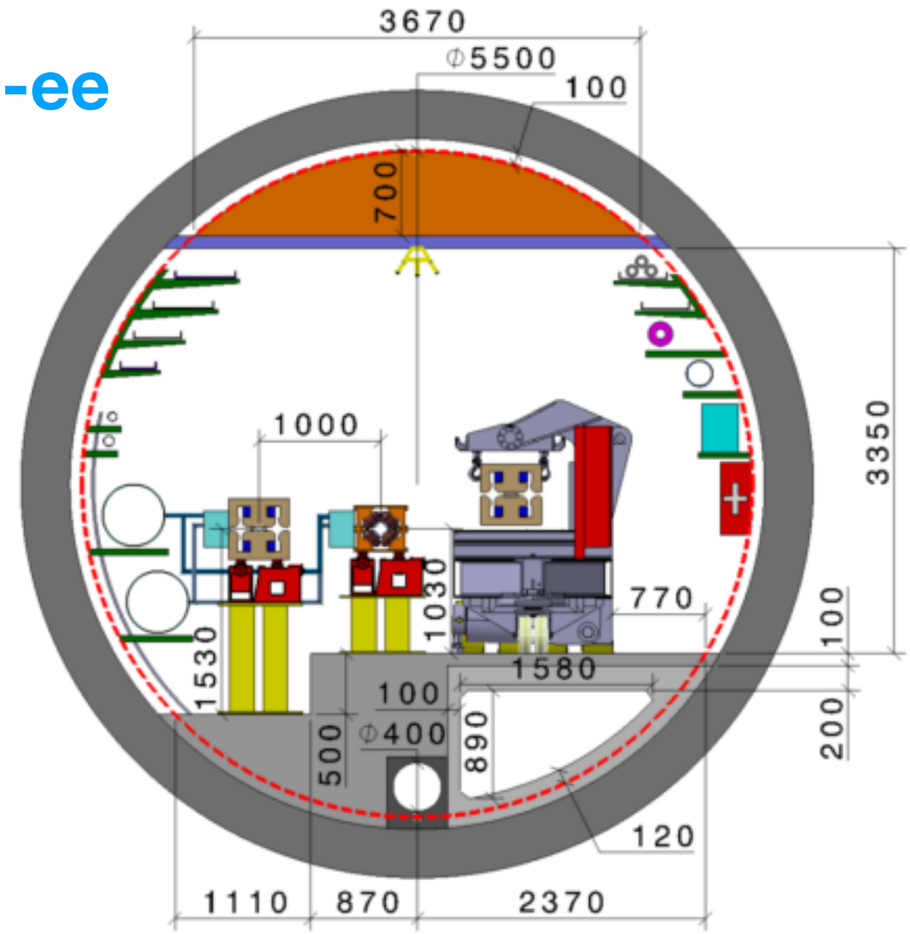
- Set of requirements and constraints, such as:
  - civil engineering feasibility and subsurface constraints
  - territorial constraints at surface and subsurface
  - nature, accessibility, technical infrastructure and resource needs and constraints
  - economic factors related to regional developments
- Baseline established, next step review of surface site locations and machine layout.
  - Total construction duration 7 years
  - First sectors ready after 4.5 years



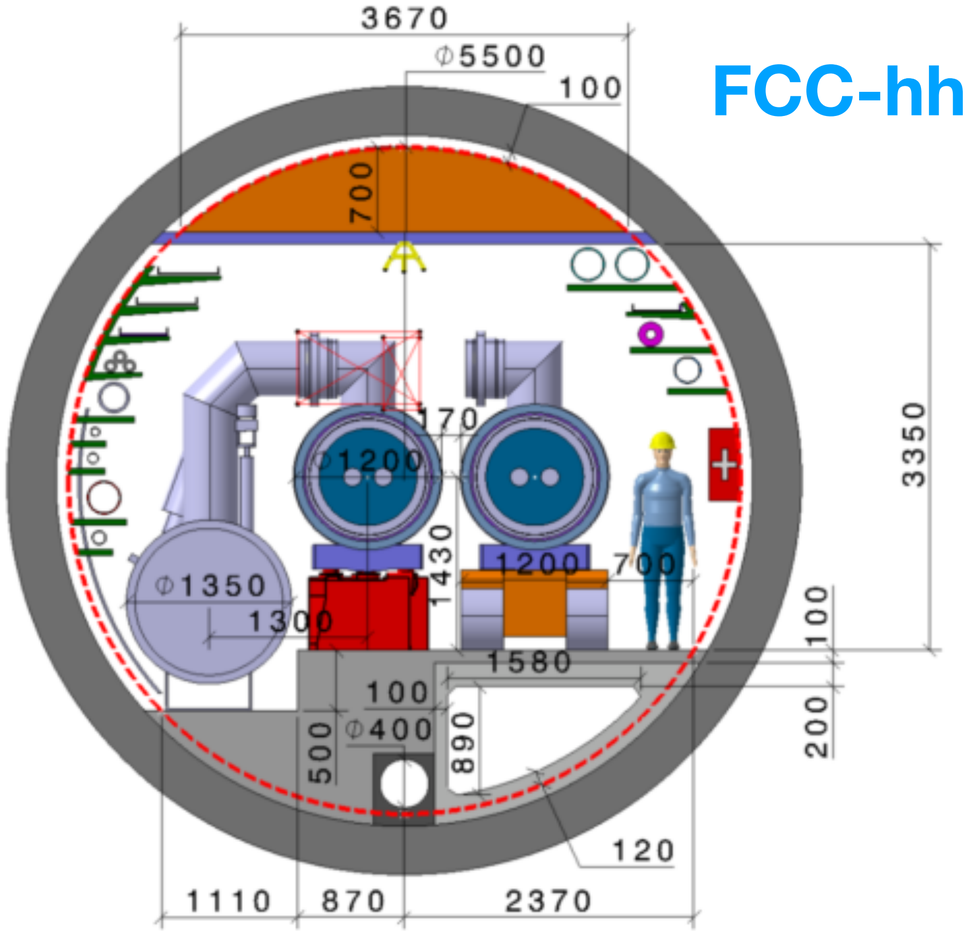
FCC tunnel

5.5m inner diameter

FCC-ee

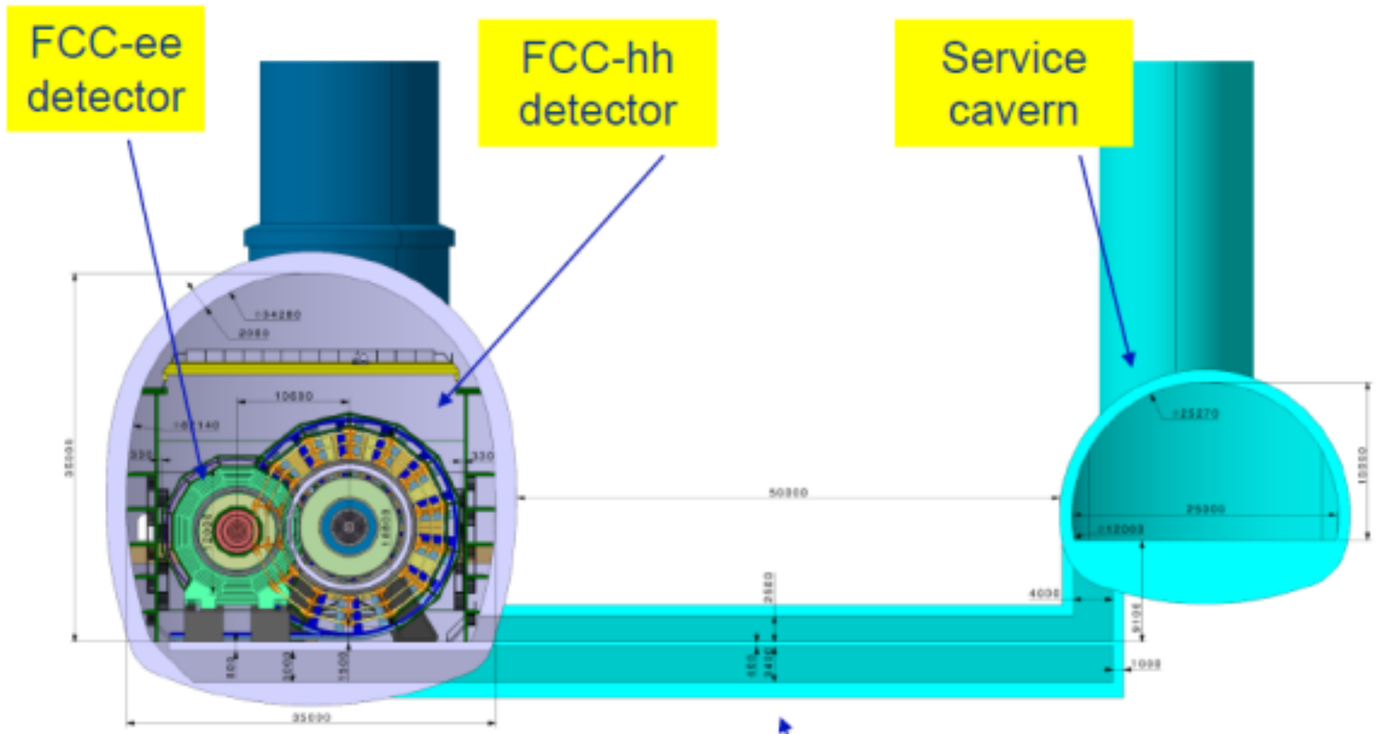


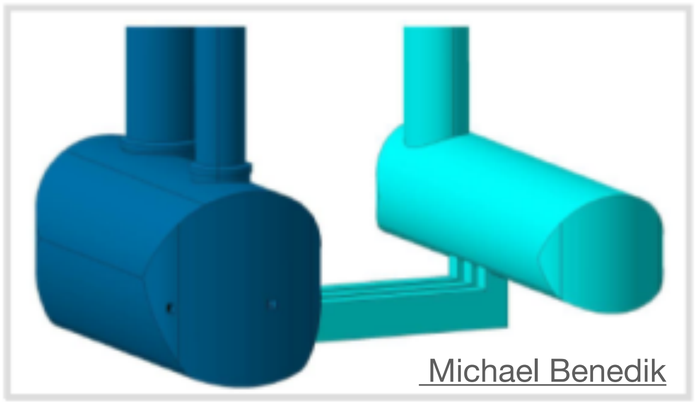
FCC-hh



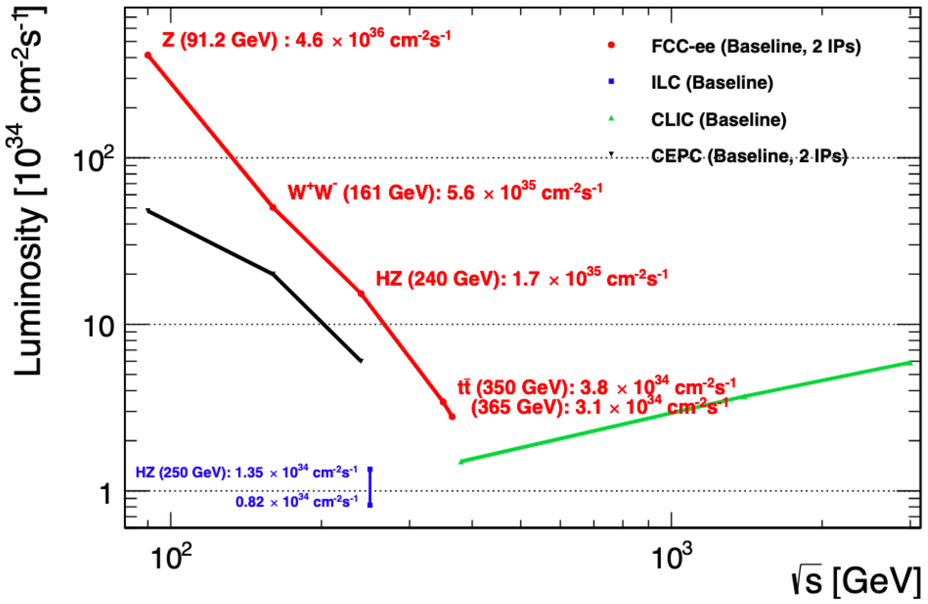
Common experimental points

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




Michael Benedik

FCC-ee

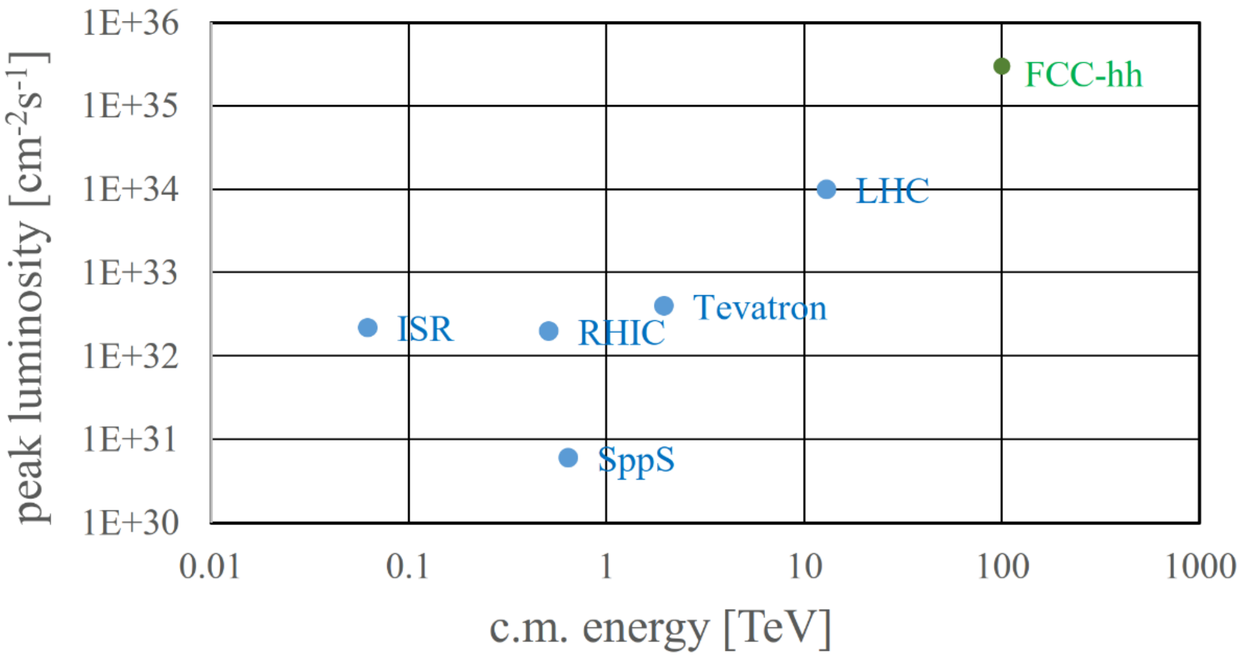


- Great energy range for the heavy particles of the Standard Model
- Complementarity with hadron (LHC, FCC-hh) and linear colliders
- Design based on lessons and techniques from previous colliders combining successful ingredients → highest luminosities & energies

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

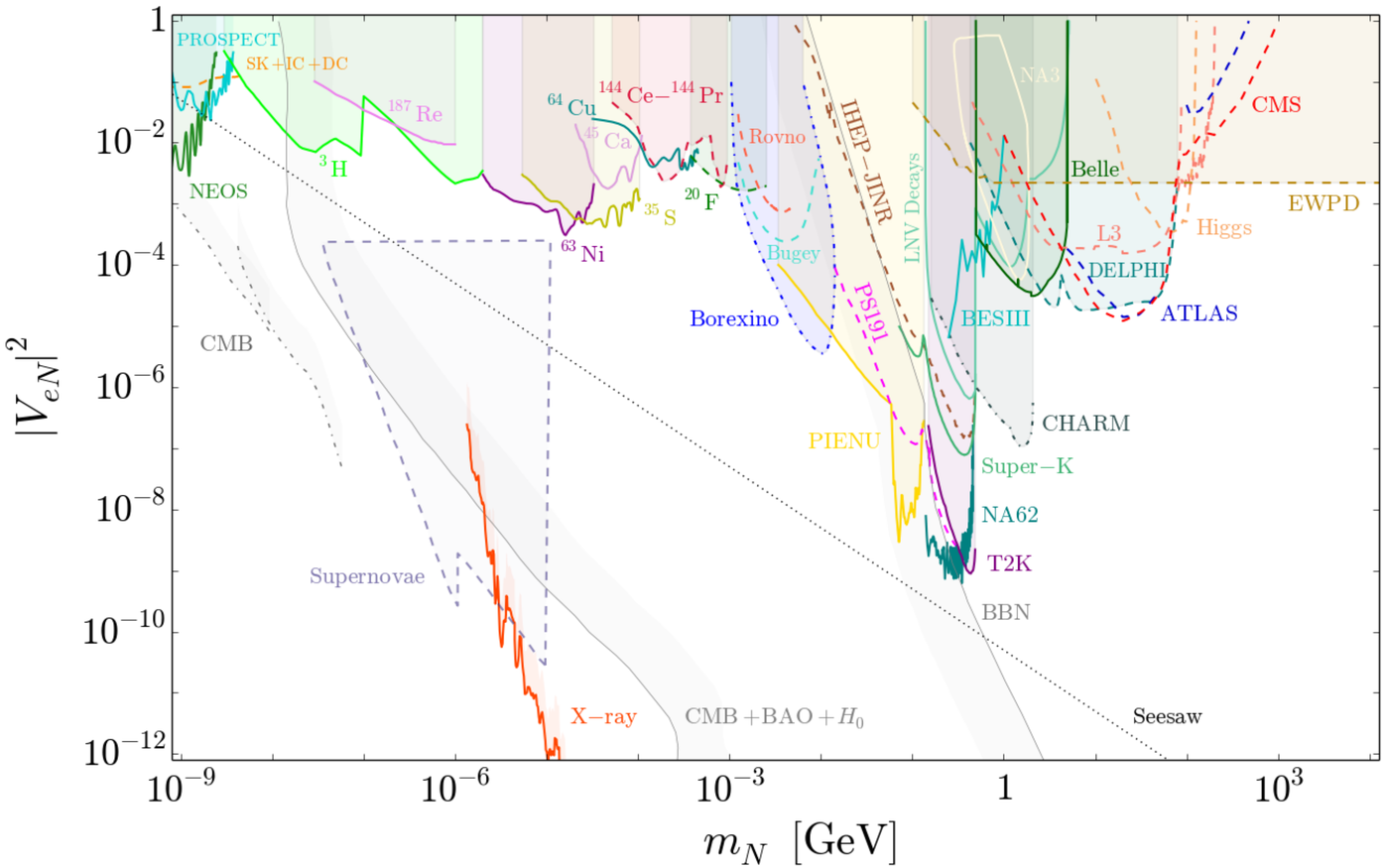
FCC-hh



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

Heavy Neutral Leptons (HNLs)

- PDG definition:
  - *Dirac or Majorana fermions with sterile neutrino quantum numbers, that are heavy enough to not disrupt the simplest Big Bang Nucleosynthesis bounds and/or unstable on cosmological timescales*
  - *Typically HNLs have mass ~MeV or higher*
  - *Searches for these particles generically set bounds on the mixing between the HNL and the active neutrinos*

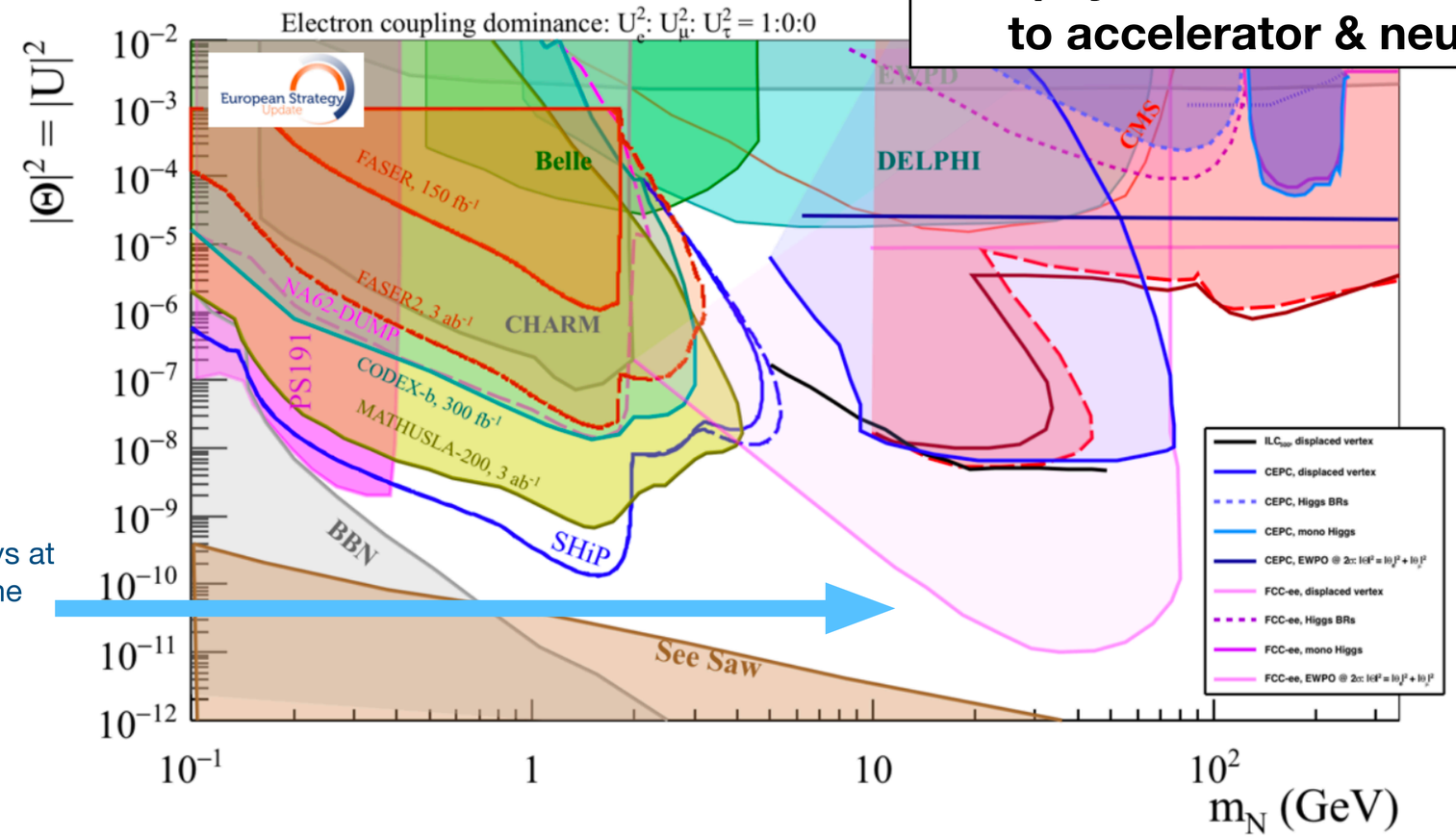


Current constraints on the electron neutrino-sterile neutrino mixing $|V_{eN}|^2$ as a function of the sterile neutrino mass m_N [Ref]

Heavy Neutral Leptons at the FCC

A flagship search

FCC probes space not constrained by astrophysics or cosmology, complementary to accelerator & neutrino prospects



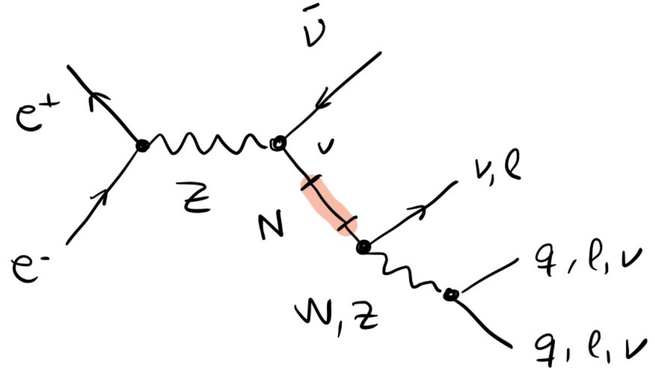
Reach for HNL decays at the Tera-Z run of the FCC-ee

90% CL exclusion limits for a HNL mixed with the electron neutrino, from the Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020 (https://cds.cern.ch/record/2691414/)

FCC-ee

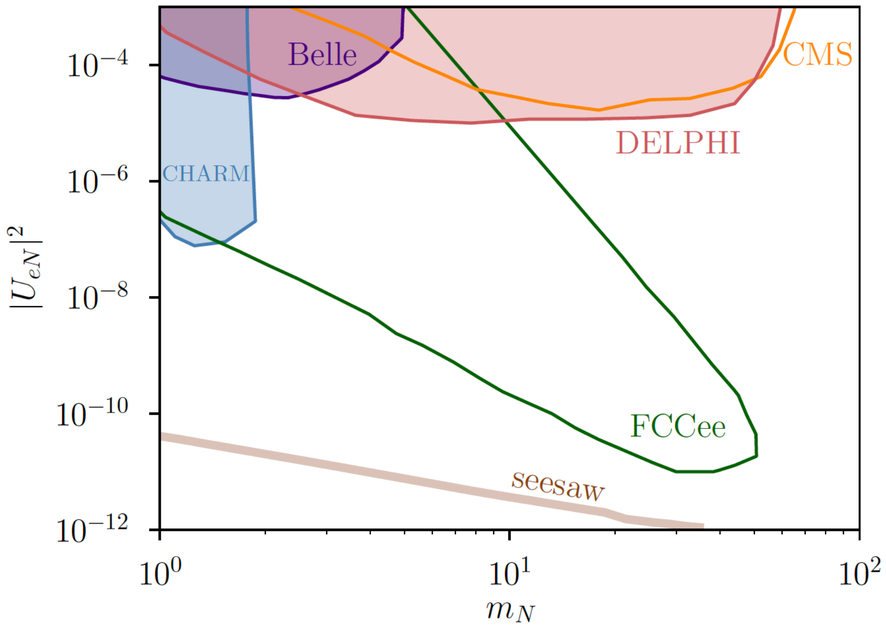
Single HNL production in Z decays

- The FCC-ee will offer an unbeatable reach for HNL at the Z-Pole:
  - $Z \rightarrow \nu N$, $N \rightarrow l\, W$ ($W \rightarrow qq$, $l\nu$)

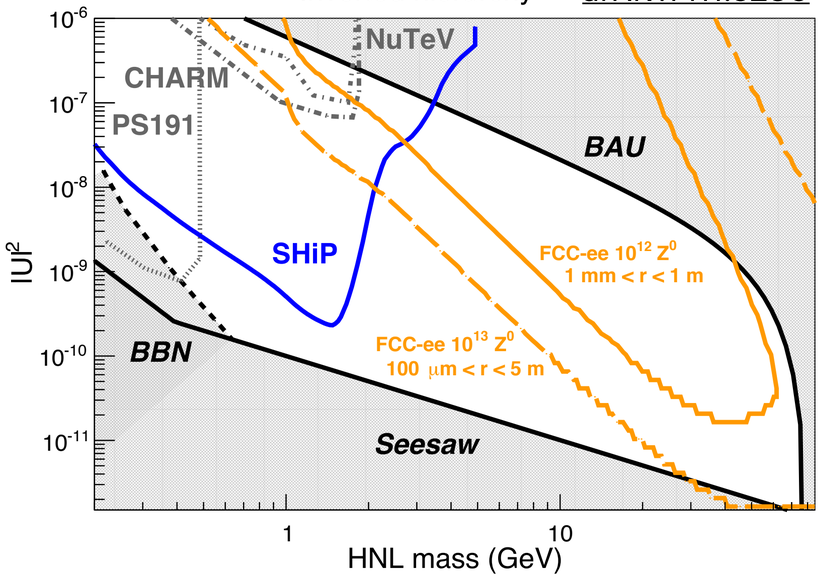


- Sensitivity above the charm mass (~1GeV) for a large range of couplings
- Good complementarity with Beam Dump Facilities

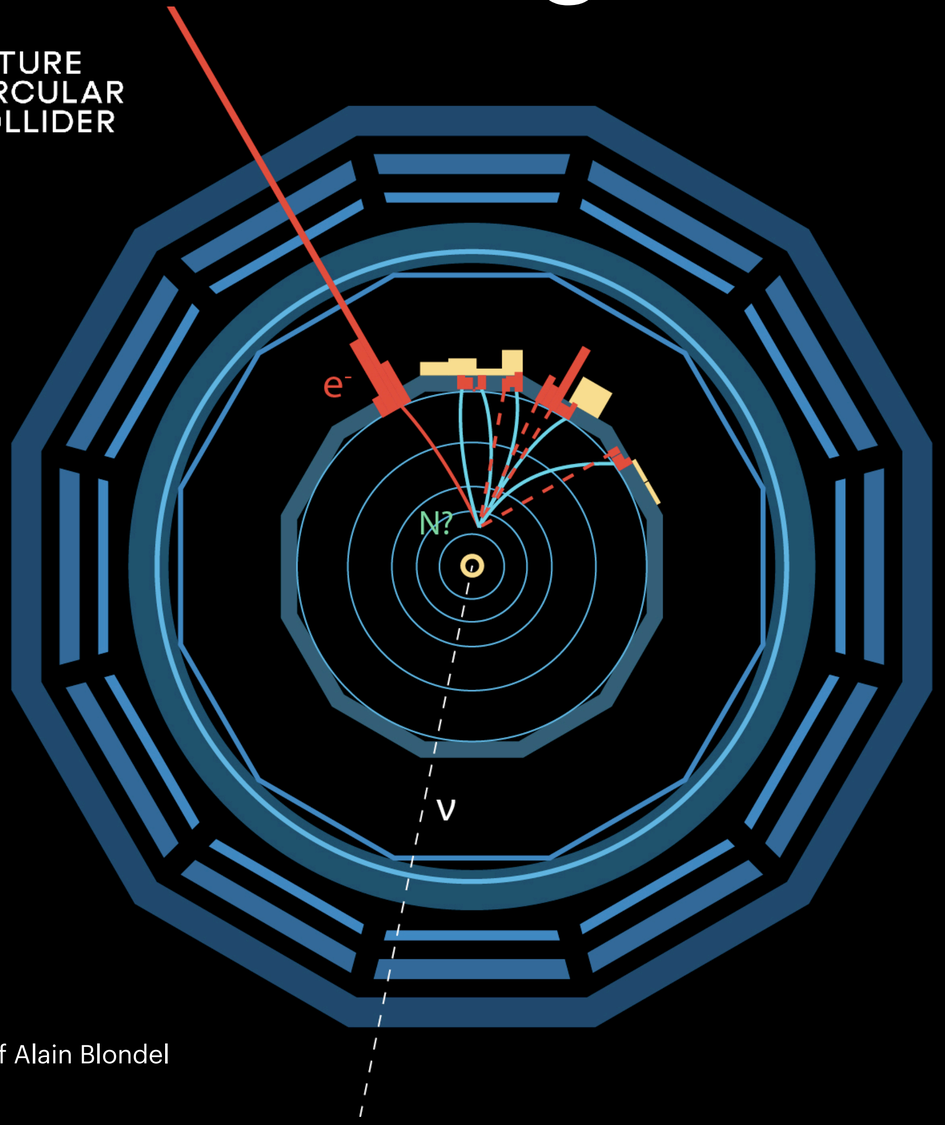
Reference



Inverted hierarchy arXiv:1411.5230



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
  - $Z \rightarrow \nu N$, $N \rightarrow lW$
    - displaced vertex search

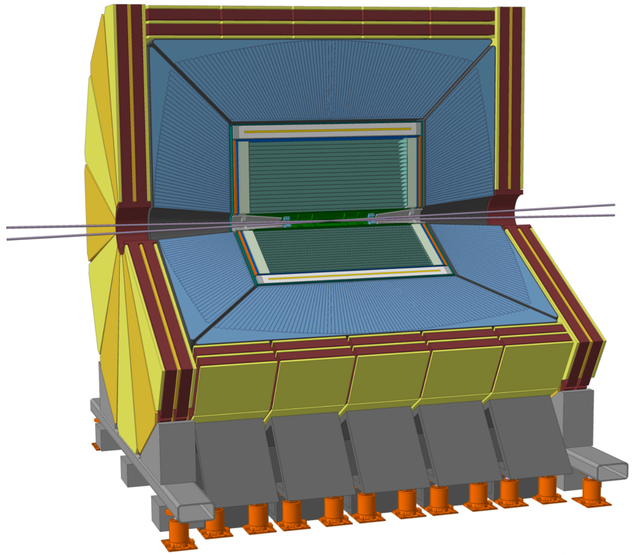
FCC-ee

Long-lived HNLs

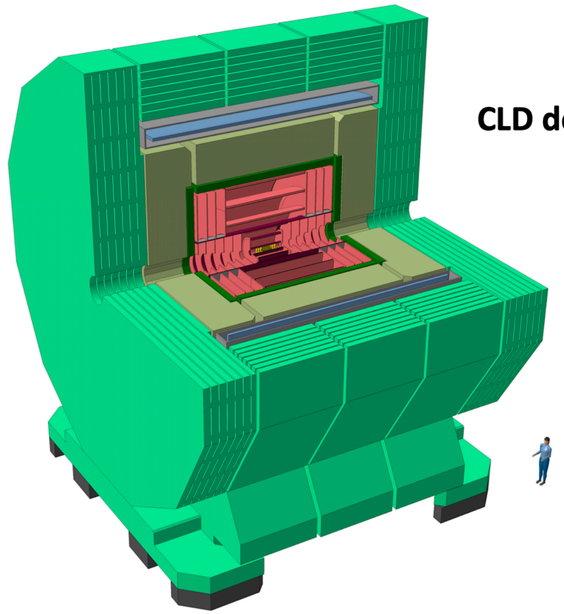
- HNL could decay **~1m away from the collision point**
  - Secondary vertex in the middle of the tracking system
  - Background-free searches
  - Instrumental and cosmic background to be studied
- For HNL with long enough lifetime → oscillations can also be studied arXiv:1709.03797

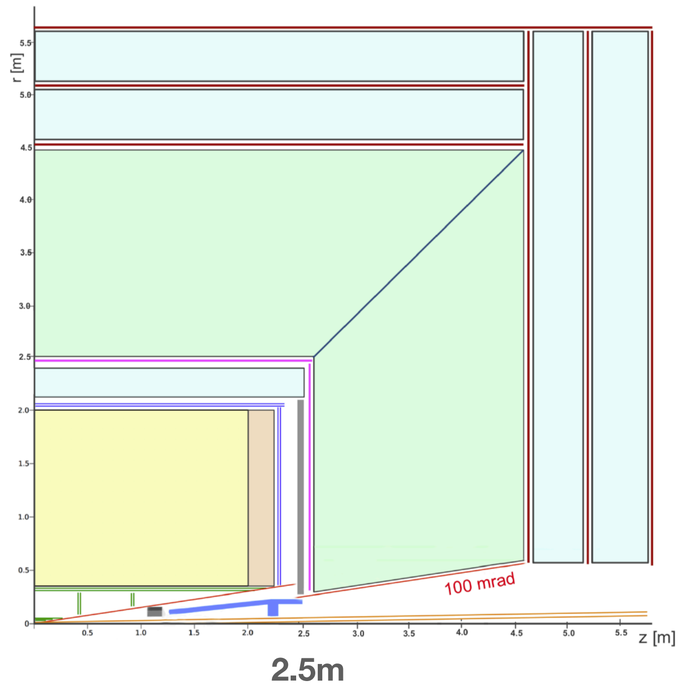
Two detector concepts for the FCC-ee

Reference

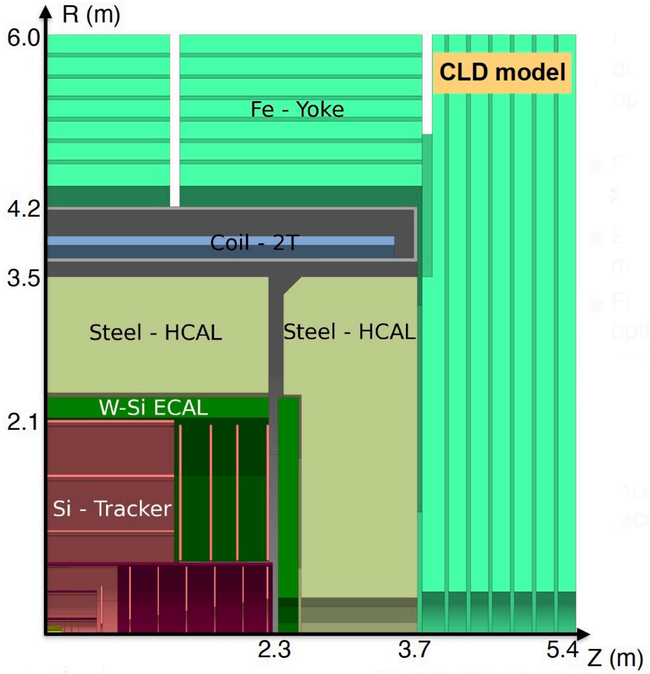


IDEA design



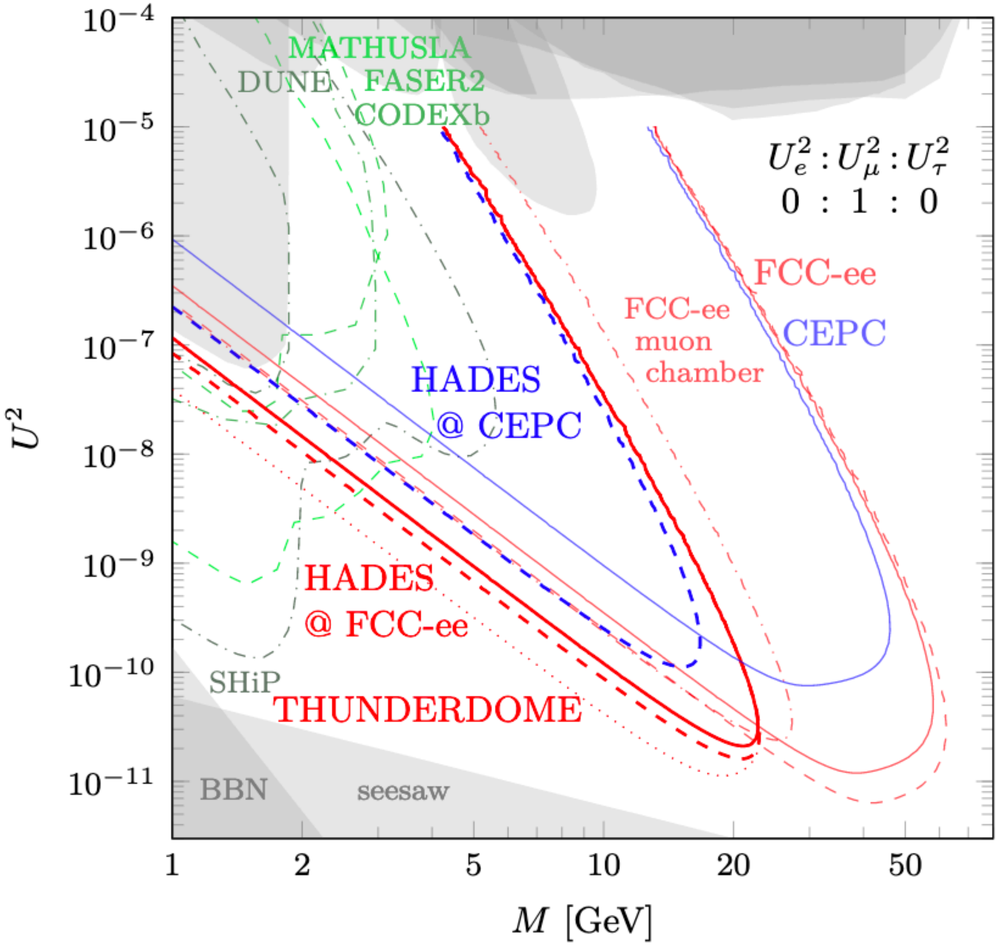


2.5m



FCC-ee: Extra detectors

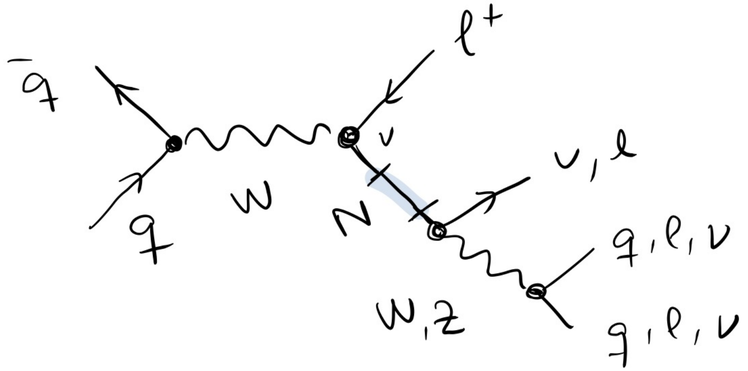
Following on additional LLP experiments at the HL-LHC



- Following the plans for different additional LLP experiments at the HL-LHC it is possible to also envision similar concepts at other future colliders
- **HADES: A long lived particle detector concept for the FCC-ee or CEPC**
- arXiv:2011.01005
- The civil engineering of the FCC-ee will have much bigger detector caverns than needed for a lepton collider (to use them further for a future hadron collider)
- Then we could install extra instrumentation (scintillation plates, RPCs?) at the cavern walls to boost the reach for HNL

FCC-hh

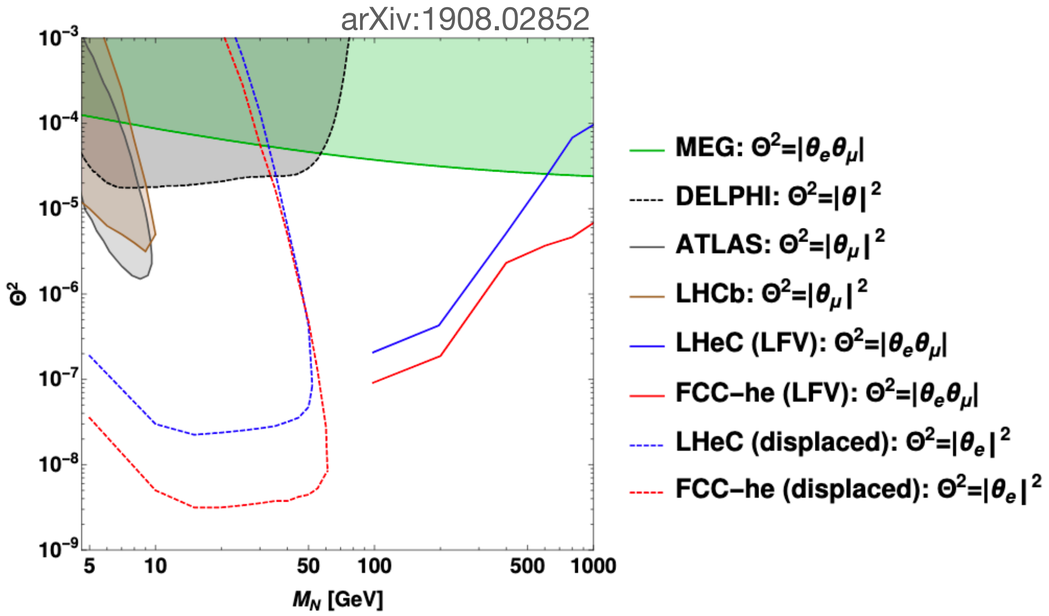
W decays



- FCC-hh high luminosity and large centre of mass energy will help probe additional parameter space
  - High mass, but mixing angles of interest to neutrino mass models not accesible
- At the 100 TeV pp, 10^{13} W bosons → HNL produced in W decays
  - Discovery signatures: three leptons, displaced vertex
  - More complex environment than FCC-ee: pile-up/backgrounds/lifetime/trigger
- **Allows for characterization both in flavour and charge of the produced neutrino**, thus information of the flavour sensitive mixing angles and a test of the fermion violating nature of the intermediate(Majorana) particle.
  - **If we find hints for HNL at the FCC-ee, the FCC-hh will help understanding more about them**

FCC-eh

Lepton-hadron collider

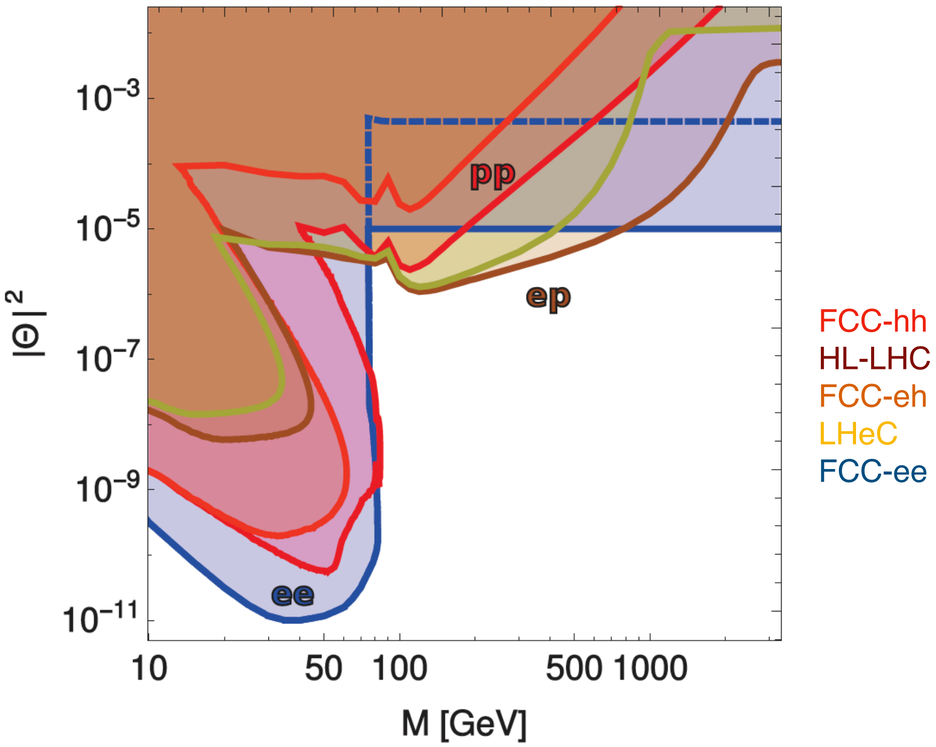


- The FCC-eh is a lepton-hadron collider operating with the FCC-hh:
  - Microscope for studying quark-gluon interactions and possible further substructure of matter
  - Will also extend the mass reach of the FCC-hh for HNL
- The FCC-eh will offer additional sensitivity for LFV
  - Also in displaced signatures (long-lived)

Complementarity

FCC-ee/-hh/-eh

arXiv:1612.02728



FCC-ee

Indirect constrains from precision SM measurements (not discussed)

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

What is next?

Get some work done!

- Now is the time to
  - Organize and properly benchmark key models
    - **Reaching out outside collider physics!**
  - Make prospective studies of physics performance at the FCC as realistic as possible
    - Including background modelling strategies and comprehensive systematic uncertainties
  - Explore detector requirements
    - To maximize coverage and fully exploit the phase space in which we are competitive

In Summary

At the FCC, a large allowed phase-space will be within reach for HNL

The complementarity of the three different stages of the FCC provides unique potential to discover and pin down these particles, and maybe solve long-standing problems of the SM

FCC probes space not constrained by astrophysics/cosmology, complementary to accelerator & neutrino prospects

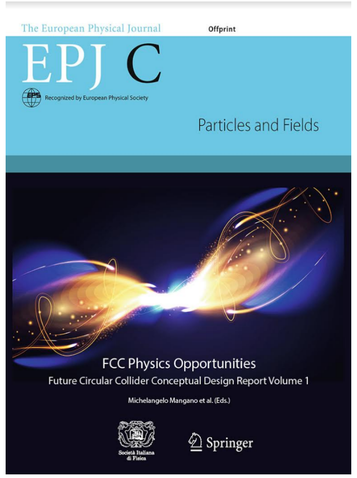
- Given the breadth of HNL, it is worth to open a conversation across disciplines
  - To tell a coherent story → **benchmarking**
  - To put observations in context within the big-picture questions we are all trying to answer
  - Cross-talk: instrumentation, technology and computing & data acquisition tools
- Within Snowmass for example, questions that can be answered by joint work between the FCC & other experiments, are being developed (Dark Matter); iDMEu https://indico.cern.ch/event/869195/
  - HNL could follow a similar approach!

Find out more

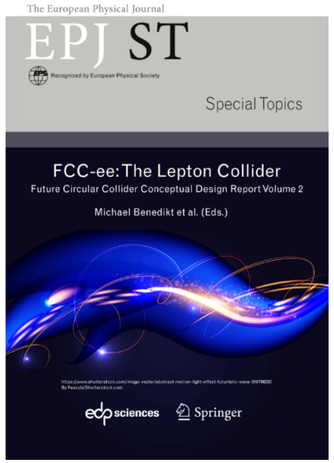
FCC documentation

- 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/

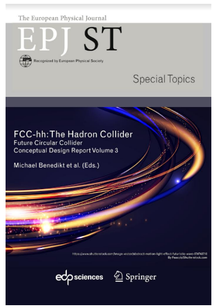
4 CDR volumes published in EPJ



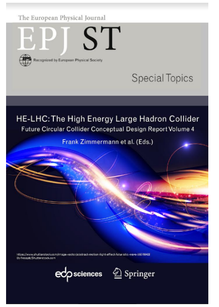
FCC Physics Opportunities



FCC-ee: The Lepton Collider



FCC-hh: The Hadron Collider



HE-LHC: The High Energy Large Hadron Collider

Credits: Many thanks to the FCC people and the experimental-complementarity fans, in particular Alain Blondel, Patrizia Azzi, Suchita Kulkarni, and Caterina Doglioni