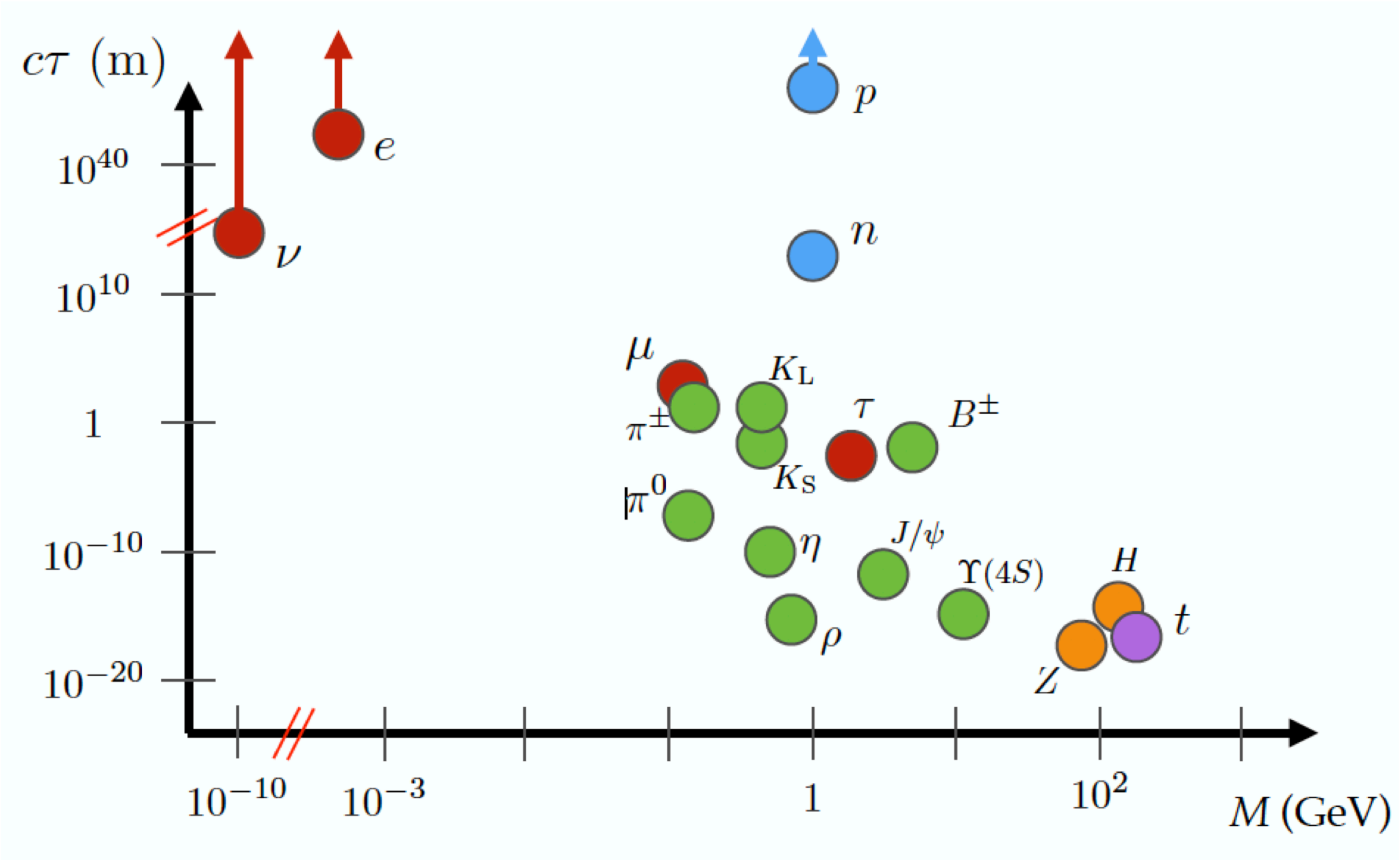
Long-lived Particles at FCC

Rebeca Gonzalez Suarez - Uppsala University

FCC Week 2021

Long-lived particles

In the context of BSM searches at colliders



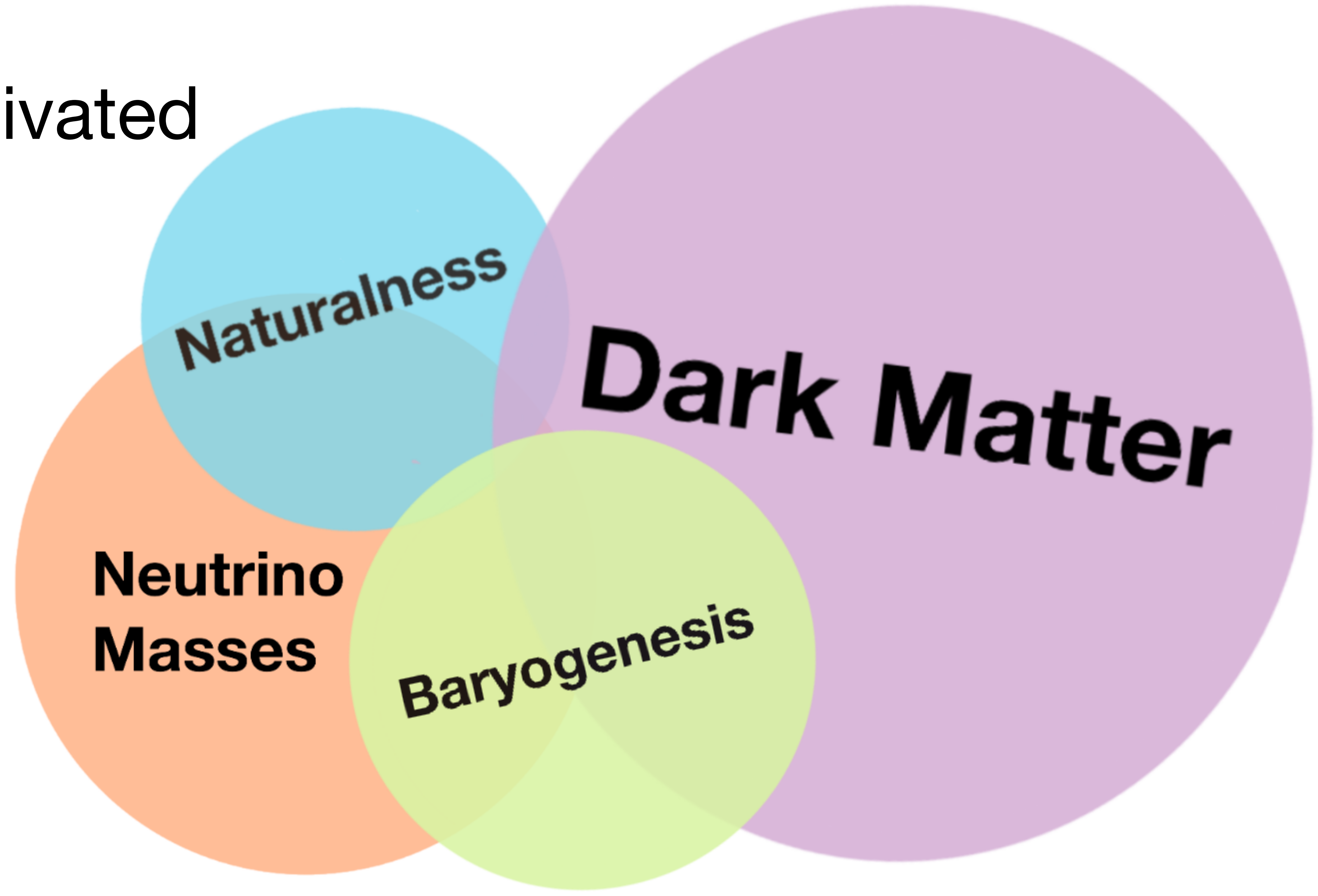
- How long the lifetime of a particle is depends on many factors, mainly **mass**, and **couplings**.
- We use LLP as umbrella term to cover particles with lifetimes long enough to travel measurable distances inside the detectors before decaying, long enough to have distinct experimental signatures

And thought many SM particles are technically long-lived, we tend to use the term to refer to **NEW particles that we have not discovered yet**

New, long-lived particles

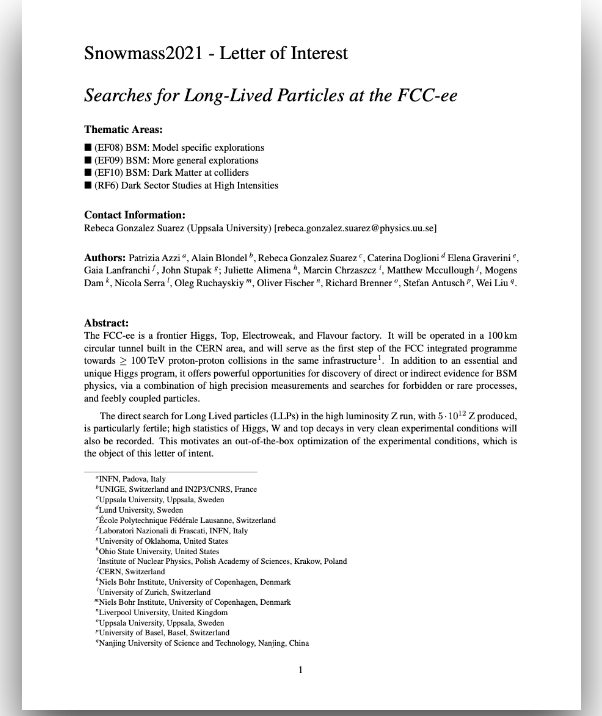
Are not a prediction of a single new theory

- Instead, they fit into virtually all proposed frameworks for BSM physics
    - Typically Feebly Interacting arXiv:2102.12143
- Theoretically, their presence is strongly motivated



Work ongoing

LLP case-study



Snowmass2021 - Letter of Interest

Searches for Long-Lived Particles at the FCC-ee

Thematic Areas:

■ (EF08) BSM: Model specific explorations
■ (EF09) BSM: More general explorations
■ (EF10) BSM: Dark Matter at colliders
■ (RF6) Dark Sector Studies at High Intensities

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Abstract:
The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100 km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards $\geq$ 100 TeV proton-proton collisions in the same infrastructure[1]. In addition to an essential and unique Higgs program, it offers powerful opportunities for discovery of direct or indirect evidence for BSM physics, via a combination of high precision measurements and searches for forbidden or rare processes, and feebly coupled particles.

The direct search for Long Lived particles (LLPs) in the high luminosity Z run, with $5 \cdot 10^{12}$ Z produced, is particularly fertile; high statistics of Higgs, W and top decays in very clean experimental conditions will also be recorded. This motivates an out-of-the-box optimization of the experimental conditions, which is the object of this letter of intent.

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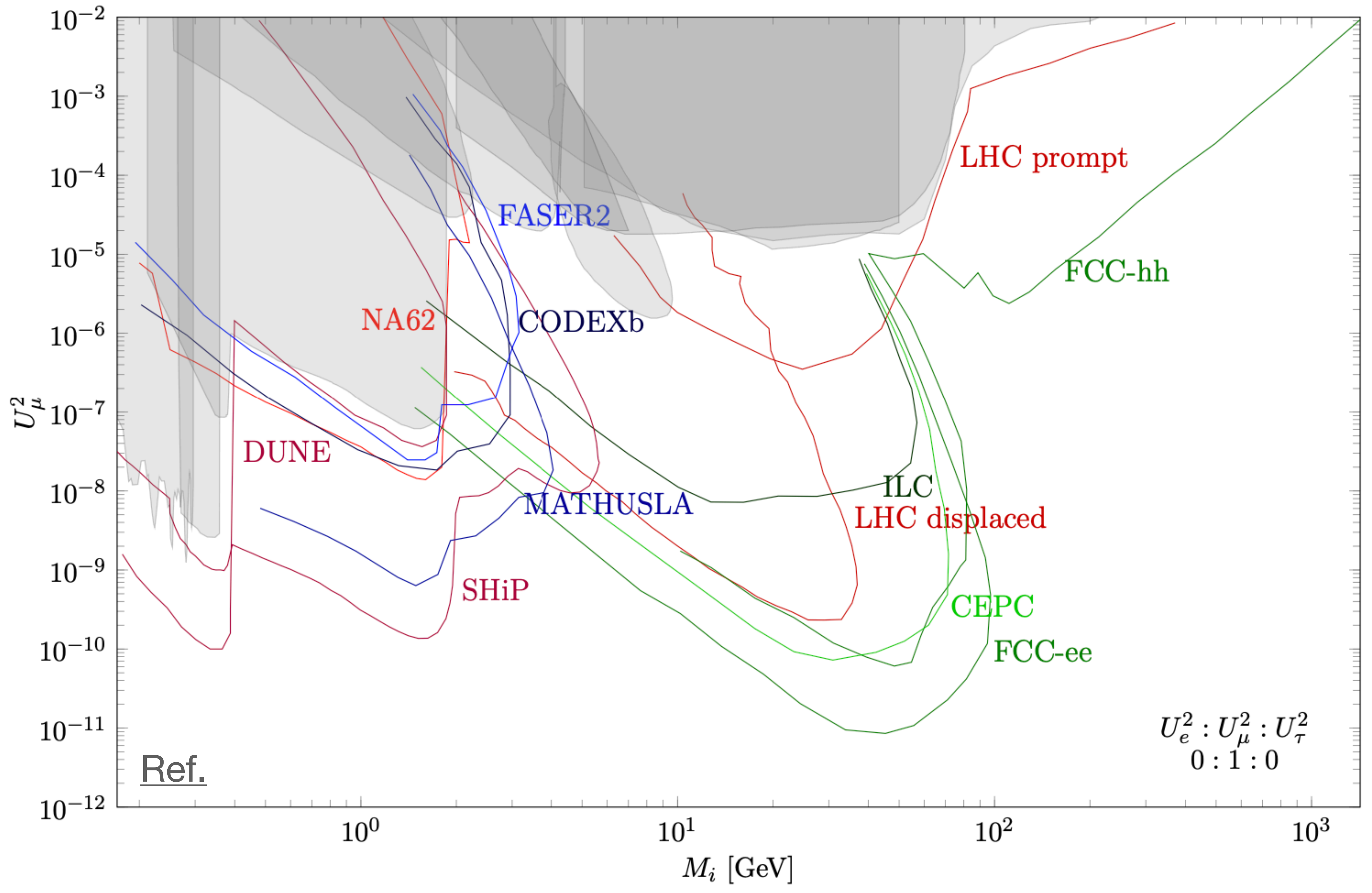
- As discussed by P. Azzi on Monday, dedicated case study for LLPs, kickstarted by a Snowmass LoI
- Activities related to it will be **highlighted in orange** and properly linked in the following in the next slides
- Gathering the interest from theory, pheno, and experimentalists (and gathering **literature** too)
- Lines of work (**P. Azzi, October 2020**):
  - Sensitivity studies for models with LLP (gen level/fast sim → FCC code)
  - Benchmarking of signatures
  - Map detector requirements (and other signature-driven needs e.g. trigger, reconstruction) → Propose optimized detector concepts?

We will see three interconnected physics examples

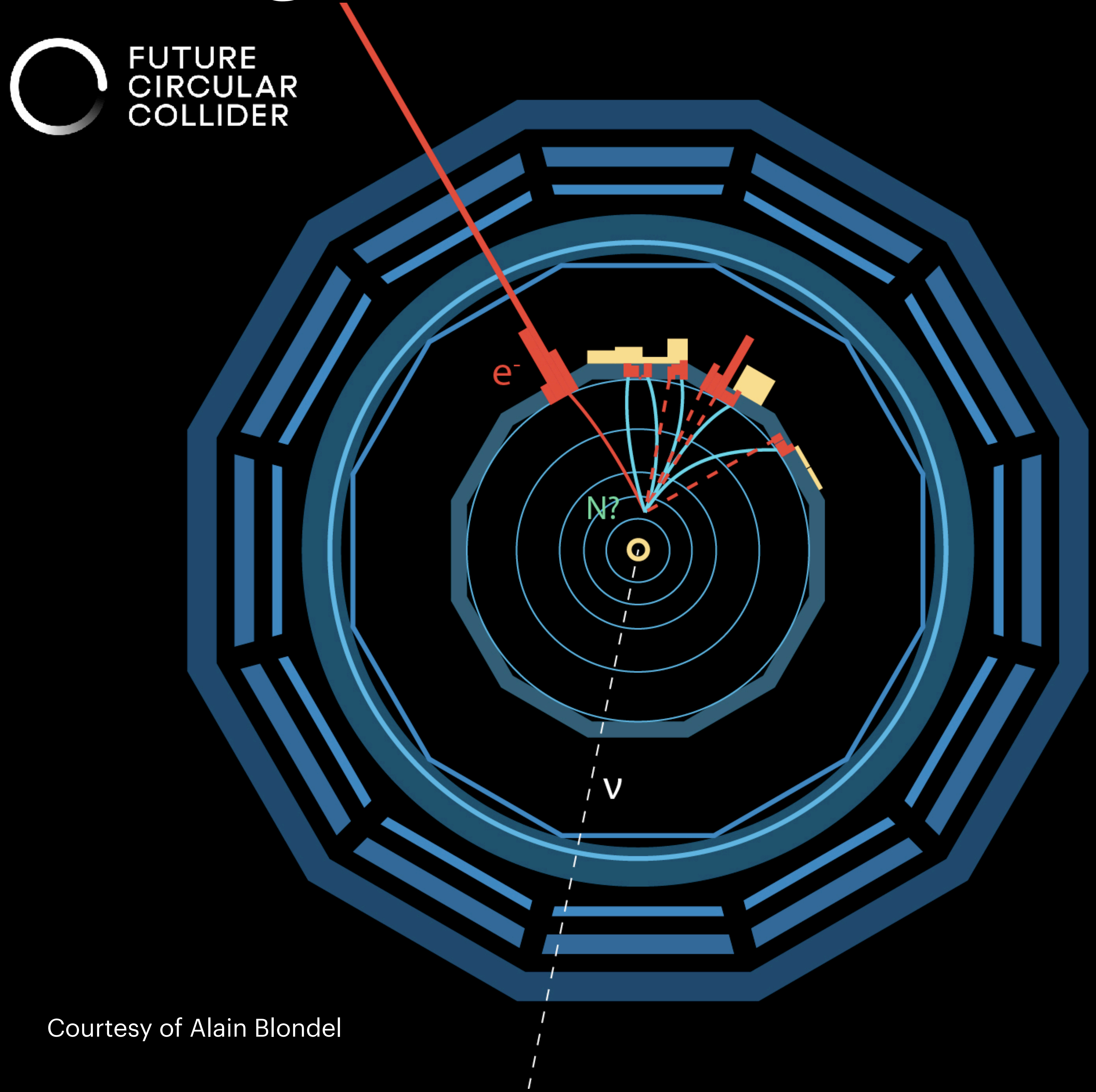
1. Heavy Neutral Leptons (HNLs)

Right handed, sterile neutrinos

- New Dirac or Majorana fermions with sterile neutrino quantum numbers, heavy enough to not disrupt the simplest Big Bang Nucleosynthesis bounds and/or unstable on cosmological timescales.
- Could answer central open questions of the SM
  - Neutrino masses
  - Baryon Asymmetry of the Universe
  - Dark Matter
- Searches typically set bounds on the mixing between the HNL and the active neutrinos



Long-lived Heavy Neutral Leptons



Courtesy of Alain Blondel

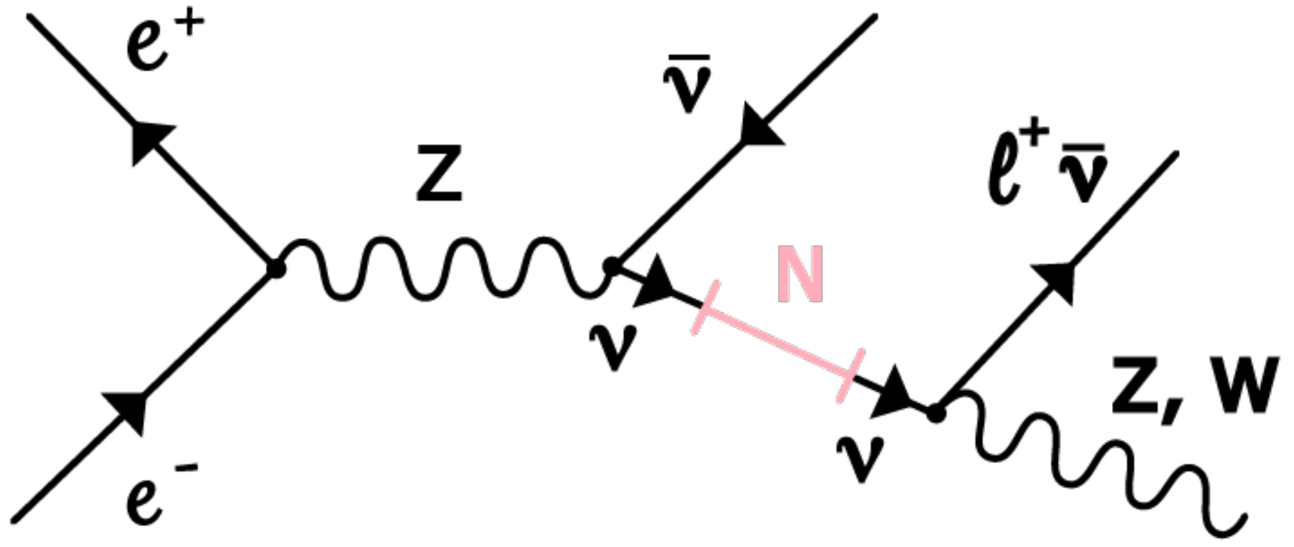
- Many of the current limits cover high neutrino mixing values
  - FCC-ee will be specially sensitive to low values
- For low values of the neutrino mixing angle, the decay length of the heavy neutrino can be significant
  - **Long-lived**
    - displaced vertex search

arXiv:1912.03058

FCC-ee

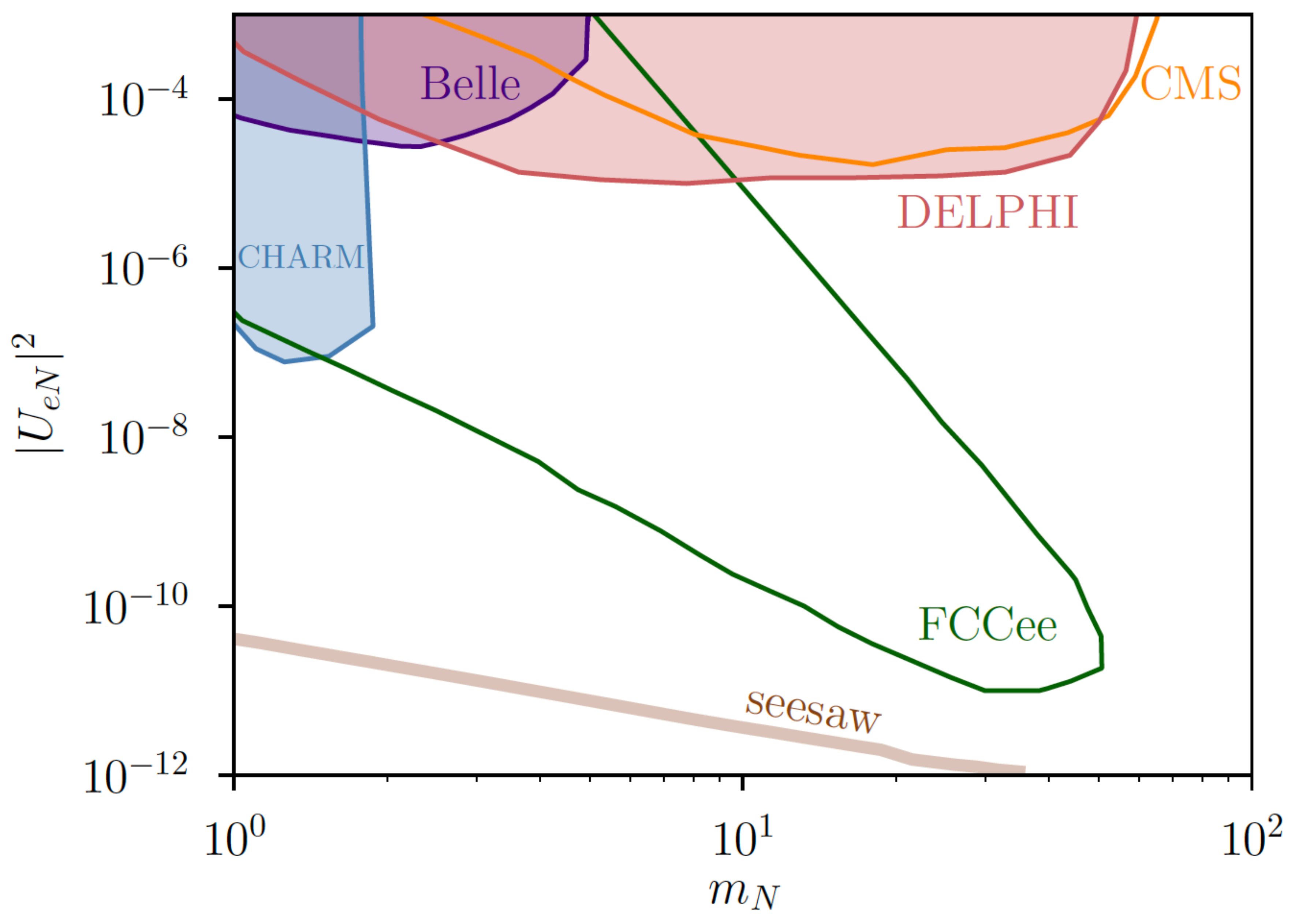
A flagship search

- FCC-ee will offer an unbeatable reach for HNL at the Z-Pole:
  - Z → νN, N → l W (W → qq, lν)

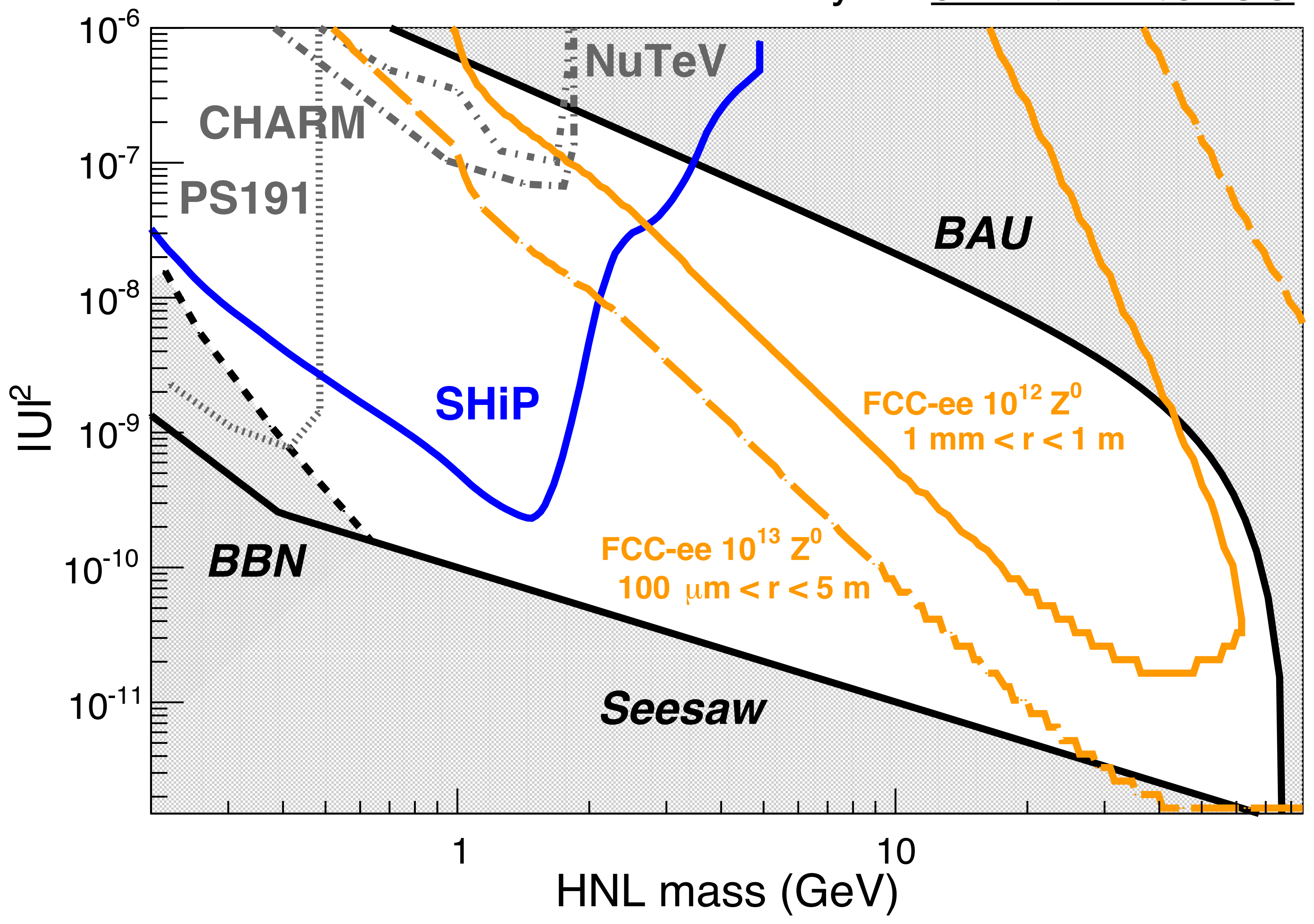


- Sensitivity above the charm mass (~1GeV) for a large range of couplings
- Good complementarity with Beam Dump Facilities
- **Discussion on generators (S. Kulkarni and R. Ruiz) Part I, Part II**

Reference



Inverted hierarchy arXiv:1411.5230



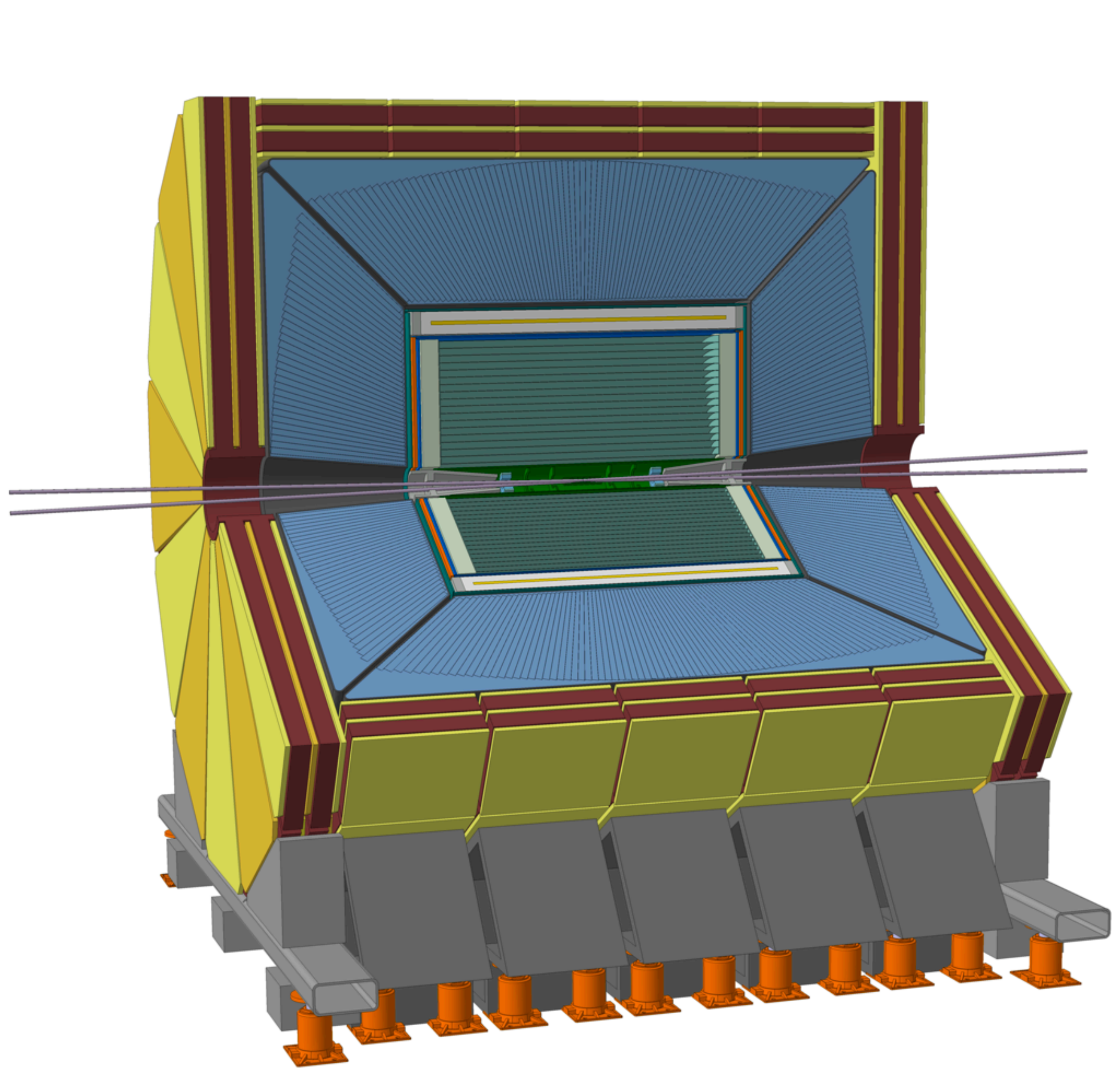
A. Das (Oct 2020)

Reference

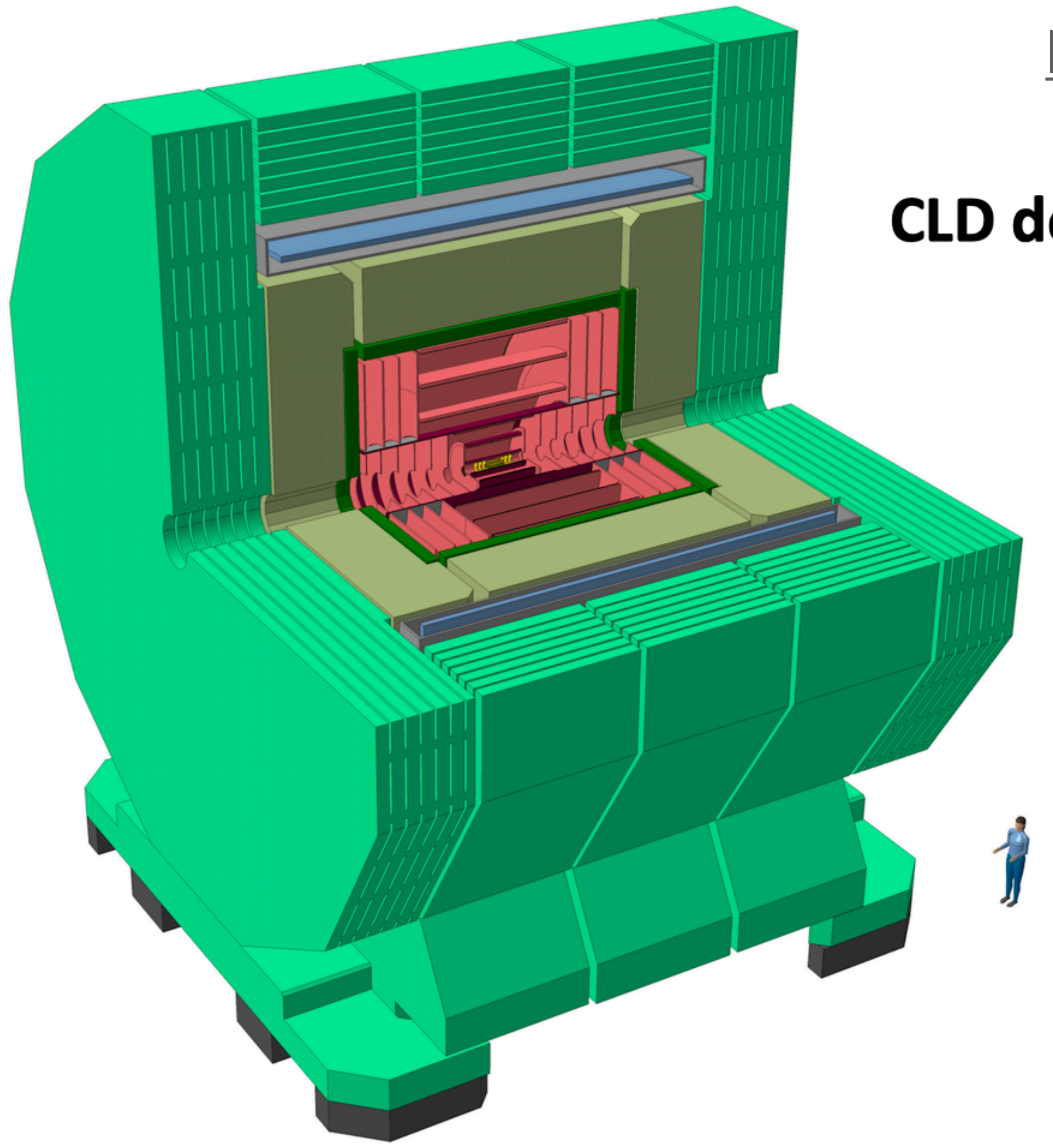
FCC-ee

HNLs in the tracker

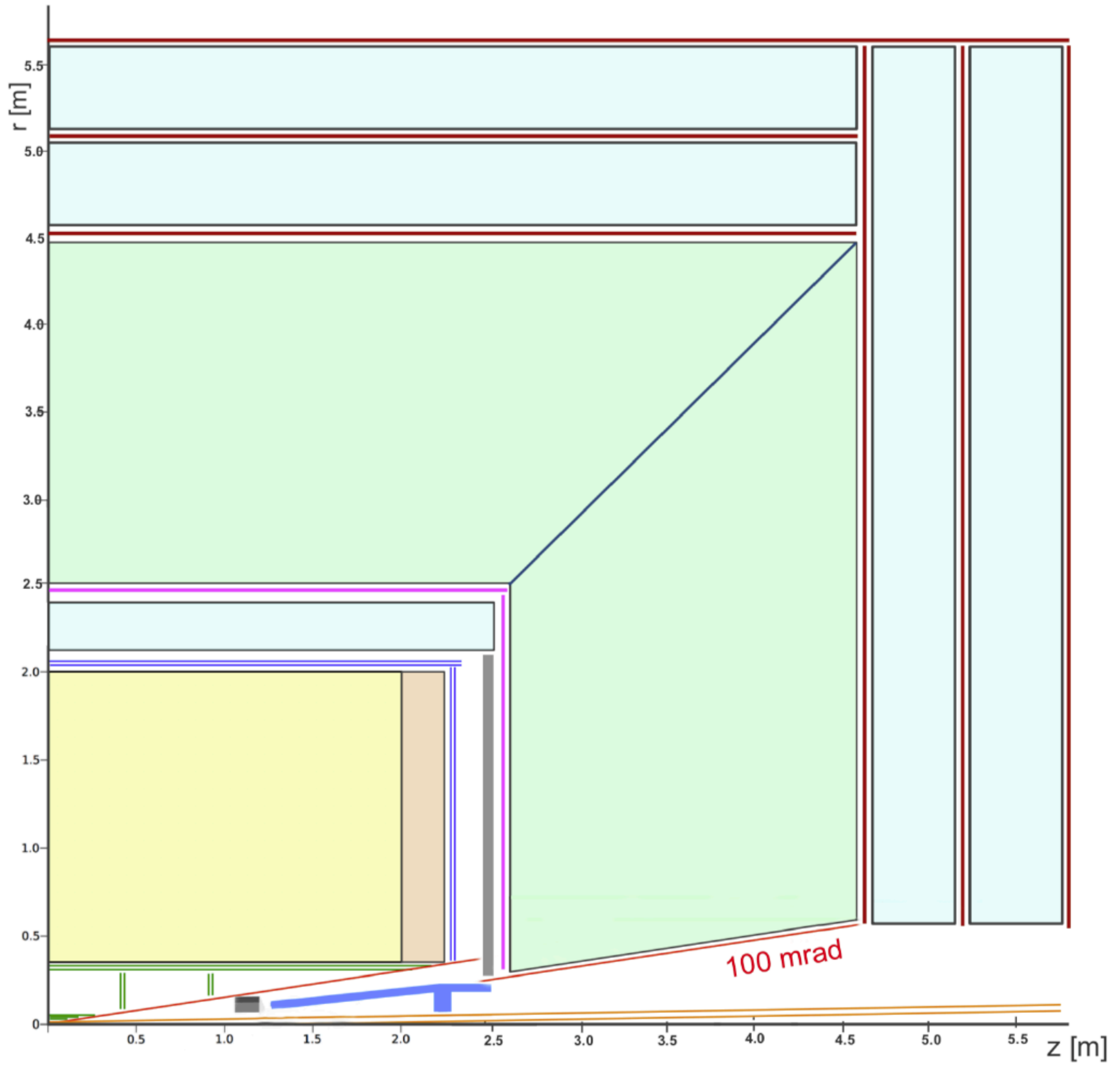
- HNL could decay **~1m away from the collision point** (arXiv:1604.02420)
  - Secondary vertex in the middle of the tracking system
  - Background-free searches
  - Instrumental and cosmic background to be studied
  - **Master thesis: Towards Vertexing Studies of Heavy Neutral Leptons with the Future Circular Collider at CERN - Rohini Sengupta, Uppsala University, June 2021.** Supervised by R. Gonzalez Suarez and S. Kulkarni
  - Shall we define Track Triggers?



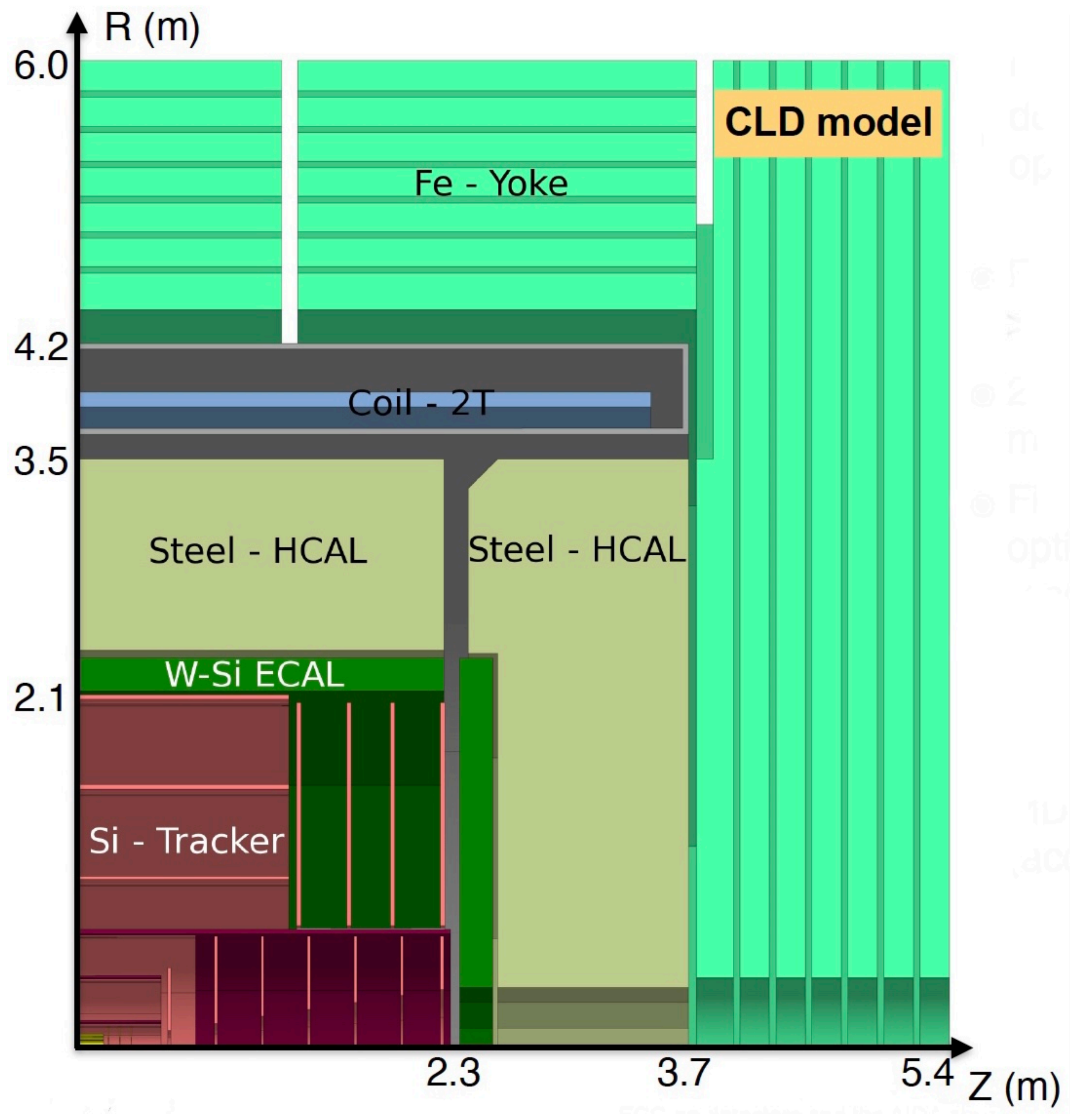
IDEA design



CLD design



2.5m



Beyond observation

Can we do more subtle studies on HNL at FCC-ee?

- Short answer: yes!
- **With enough luminosity (possible at the Tera-Z run) it would be possible to distinguish between Majorana or Dirac fermions**
  - A majorana mass term will bring up different results in two observables (Z→νN, N→l W channel) connected to two case-studies:
    - **lepton forward-backward charge asymmetry:** Important to distinguish the leading lepton charge (may be complicated if there is large displacement beyond the tracker)
    - **polarization measurement:** using the leading lepton momentum distributions, independently of the charge
      - arXiv:2105.06576
- For HNL with long enough lifetime → **neutrino oscillations** can be studied
  - arXiv:1709.03797

arXiv:2105.06576v2 [hep-ph] 31 May 2021

FERMILAB-PUB-21-227-T, NUHEP-TH/21-03

Z-Boson Decays into Majorana or Dirac (Heavy) Neutrinos

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We computed the kinematics of Z-boson decay into a heavy–light neutrino pair when the Z-boson is produced at rest in e^+e^- collisions, including the subsequent decay of the heavy neutrino into a visible final state containing a charged-lepton. We concentrated on heavy-neutrino masses of order dozens of GeV and the issue of addressing the nature of the neutrinos – Dirac fermions or Majorana fermions. We find that while it is not possible to tell the nature of the heavy and light neutrinos on an event-by-event basis, the nature of the neutrinos can nonetheless be inferred given a large-enough sample of heavy–light neutrino pairs. We identify two observables sensitive to the nature of neutrinos. One is the forward-backward asymmetry of the daughter-charged-leptons. This asymmetry is exactly zero if the neutrinos are Majorana fermions and is non-zero (and opposite) for positively- and negatively-charged daughter-leptons if the neutrinos are Dirac fermions. The other observable is the polarization of the heavy neutrino, imprinted in the laboratory-frame energy distribution of the daughter-charged-leptons. Dirac neutrinos and antineutrinos produced in e^+e^- collisions at the Z-pole are strongly polarized while Majorana neutrinos are at most as polarized as the Z-bosons.

I. INTRODUCTION

Spin one-half massive fermions in four spacetime dimensions can be classified into two types: Majorana fermions and Dirac fermions. Majorana fermions are self-conjugate; they are their own antiparticles. Dirac fermions are not. A massive Dirac field describes four independent degrees of freedom, a massive Majorana field describes two independent degrees of freedom. Dirac fields are complex and can transform under complex representations of symmetry groups (gauged or global). Majorana fields are, in some sense, real and can only transform under real representations of unbroken symmetries (gauged or global).

All known fundamental fermions are massive, except, at most, the lightest of the three neutrinos. With the exception of the neutrinos, all have nonzero electric charge. Hence, the charged leptons (e, μ, τ) and all quarks are Dirac fermions. Experimental data to date are agnostic concerning the nature of the neutrinos – Majorana or Dirac fermions.

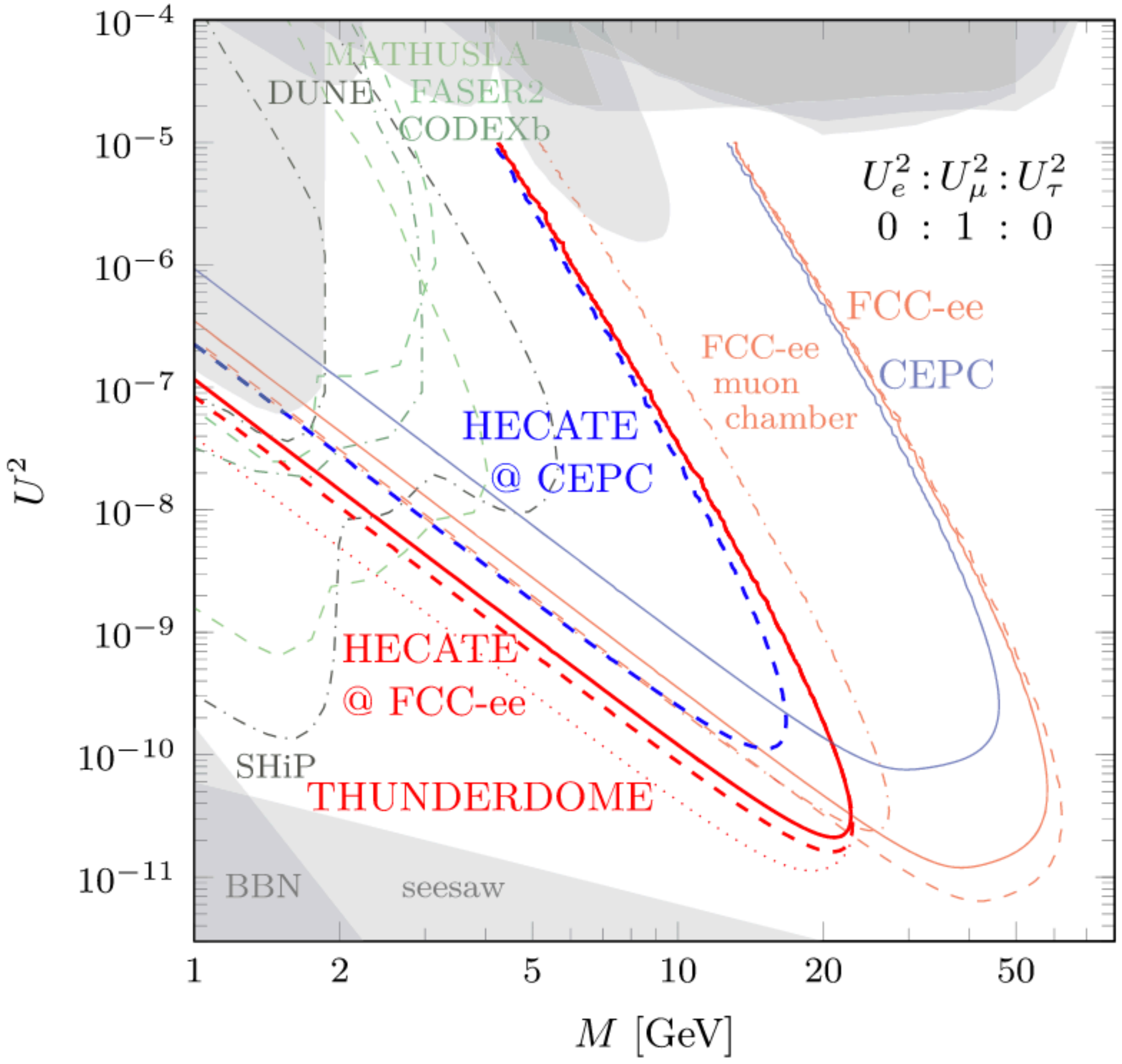
The traditional way to probe the nature of neutrinos is to test the conservation of lepton number (see, for example, [1, 2]). Majorana neutrinos, since they are self-conjugate, cannot be charged under the lepton-number symmetry, rendering it, necessarily, an approximate symmetry. Evidence for the violation of lepton-number symmetry (by two units) would translate, almost necessarily, into proof that neutrinos are Majorana fermions [3–5] (see also [6] for a modern discussion). The most powerful probes of lepton-number violation are low-energy particle and nuclear physics processes, including searches for neutrinoless double-beta decay, $(\mu^- \to e^+)$-conversion in nuclei, and forbidden meson decays (e.g. $K^+ \to \pi^-\mu^+\mu^+$). No unambiguous experimental evidence for lepton-number violation has been found yet [7].

The physics behind nonzero neutrino masses remains unknown. One can, however, affirm that nonzero neutrino masses imply the existence of new particles (for an overview see, for example, [8]). The properties – spin, mass, charge – of these new particles is currently unknown and the subject of extensive theoretical and experimental particle physics research. Information on the nature of neutrinos is expected to illuminate the origin of neutrino masses in a very fundamental way.

New neutral fermions are common side effects of the mechanism responsible for nonzero neutrino masses. The popular Type-I seesaw mechanism [9–14], for example, posits the existence of at least two gauge-singlet fermion fields in addition to the known matter fields of the Standard Model. These are allowed nonzero Majorana-mass terms and couple to the active neutrinos ν_e, ν_μ, ν_τ via Yukawa interactions. After electroweak symmetry breaking, all neutral fermions – linear combinations of the active neutrinos and the new degrees of freedom – acquire masses, all are Majorana fermions, and all couple with different strength to the electroweak gauge bosons and the Higgs boson. In the traditional Type-I seesaw, the neutral fermions "split" into three mostly-active neutrinos that are very light and at least two much heavier states that are predominantly composed of gauge-singlet fermions. We refer to the former as light neutrinos and the latter as heavy neutrinos. In this scenario, the couplings of the heavy neutrinos are related

FCC-ee: Extra detectors

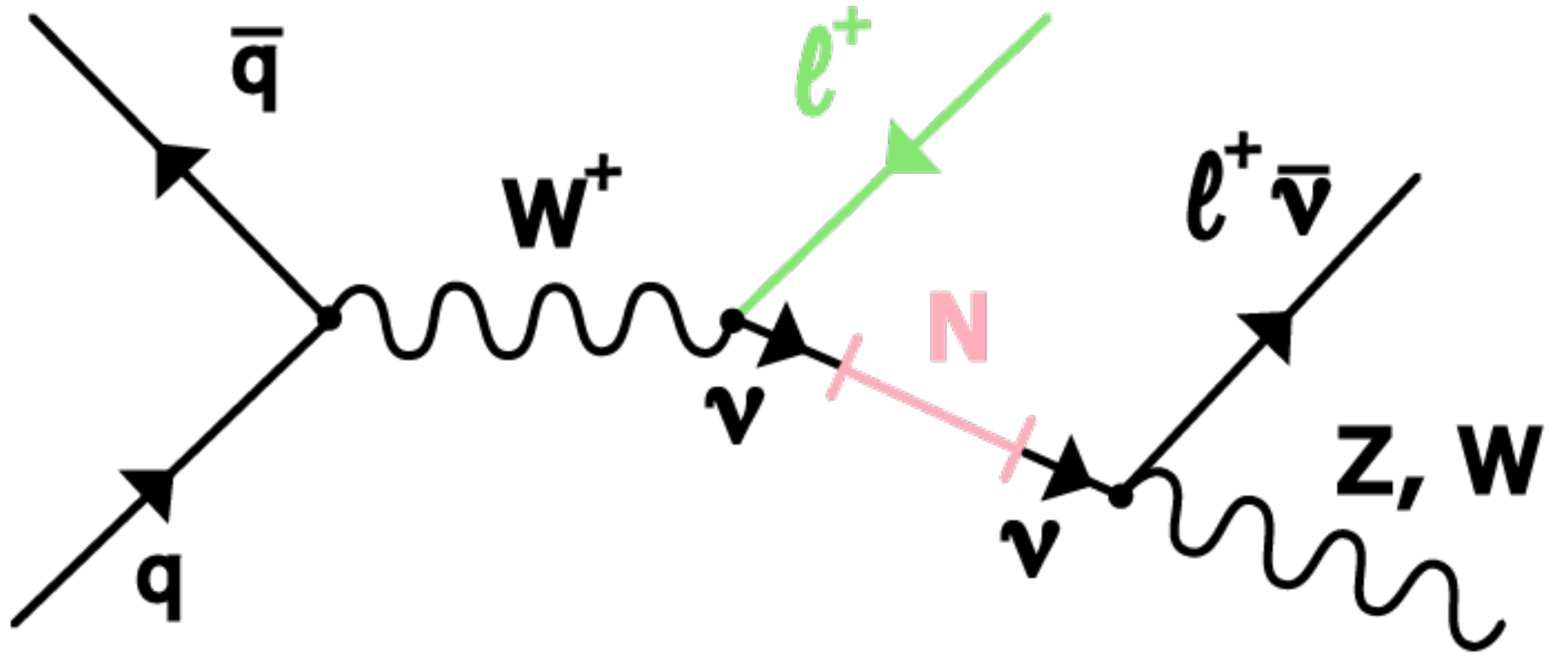
Following on additional LLP experiments at the HL-LHC



- It is possible to also envision similar concepts at other future colliders
- **HECATE (aka HADES): A long lived particle detector concept for the FCC-ee or CEPC**
  - arXiv:2011.01005, Eur. Phys. J. C 81, 546 (2021)
- 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

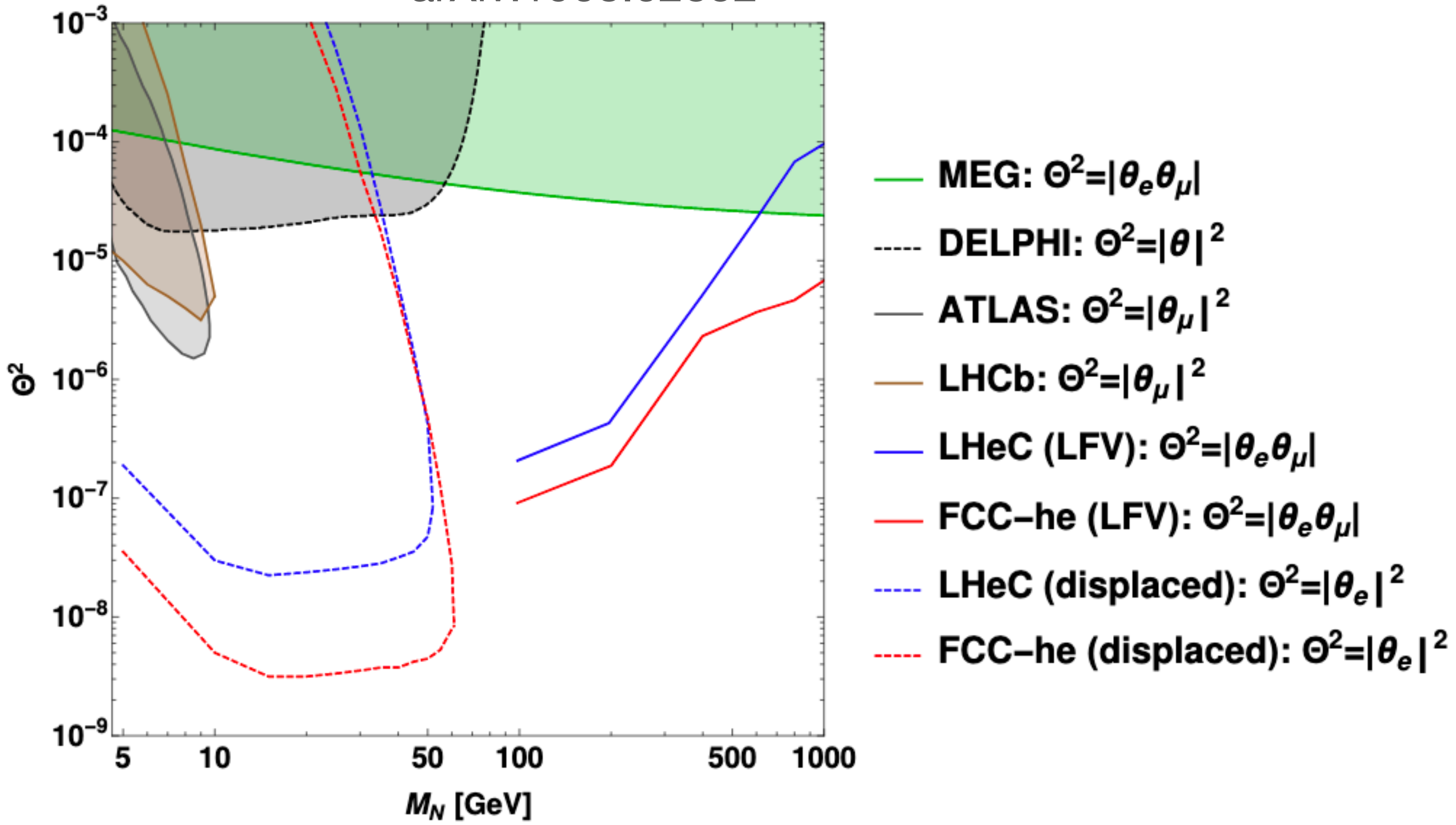


- The high luminosity and large centre of mass energy at the FCC-hh will help probe additional parameter space
  - High mass, but mixing angles of interest to neutrino mass models not accesible
- At the 100 TeV pp, 10^{13} W bosons → HNL produced in W decays
  - Discovery signatures: three leptons, displaced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

FCC-eh

Lepton-hadron collider

arXiv:1908.02852

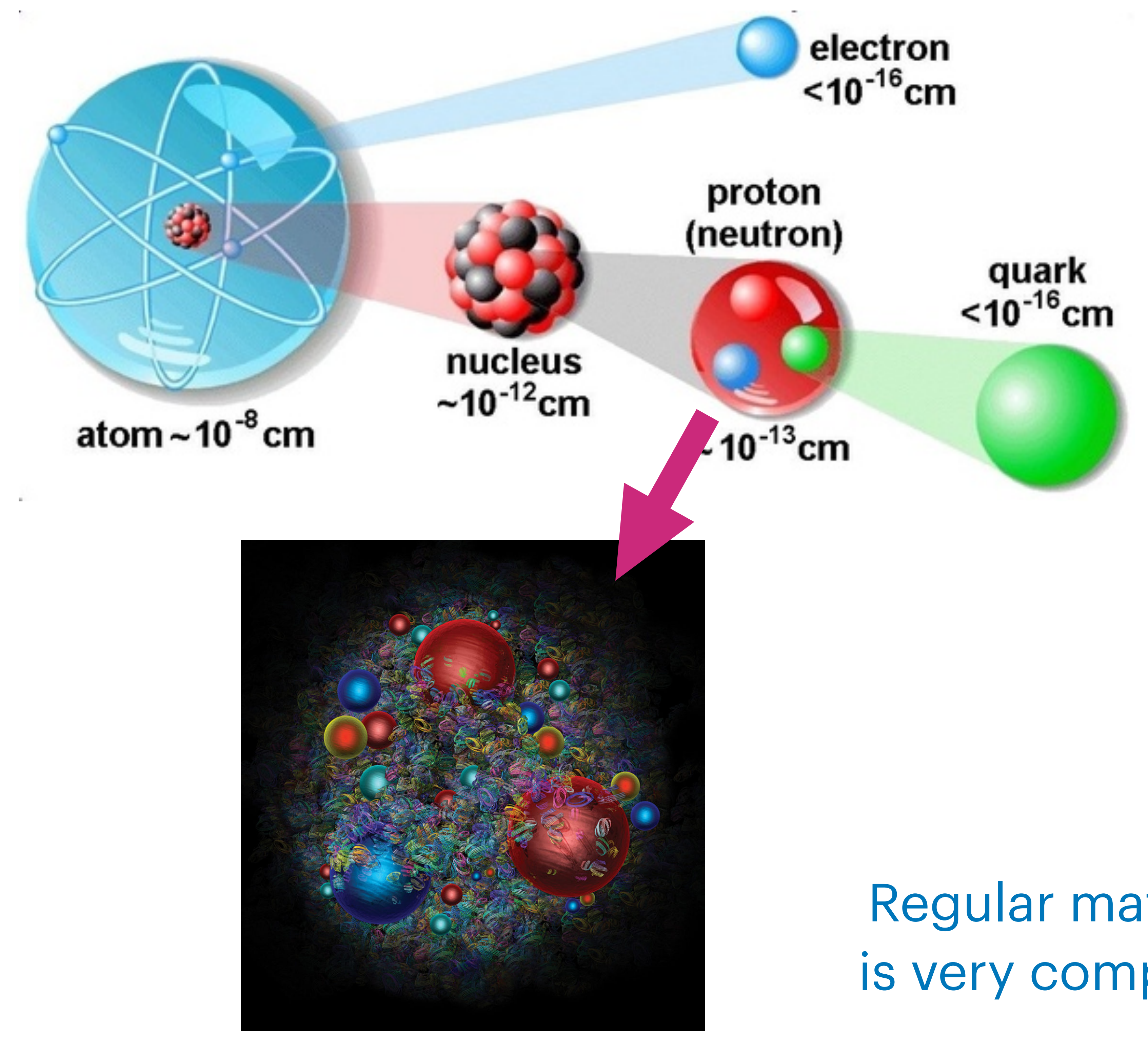


- The FCC-eh will also extend the mass reach of the FCC-hh for HNL
- The FCC-eh will offer additional sensitivity for LFV
    - Also in displaced signatures (long-lived)

2. Hidden sectors

Especially dark!

- New particles and forces could exist at accesible energy scales, but just not interact or doing it very weakly with us
- There could tiny couplings of these new particles with SM particles (the Higgs boson being one of the prime candidates) called “portals”, that would give us subtle signs to follow
- When there is a small coupling → Long-lived signature!
- Dark Matter is a prime use-case: we can propose a Dark Sector which almost does not interact with the SM but that is similarly complex
- In the context of Dark Sectors there are many Long-lived signatures that arise, some of them quite exciting, like dark showers, or…

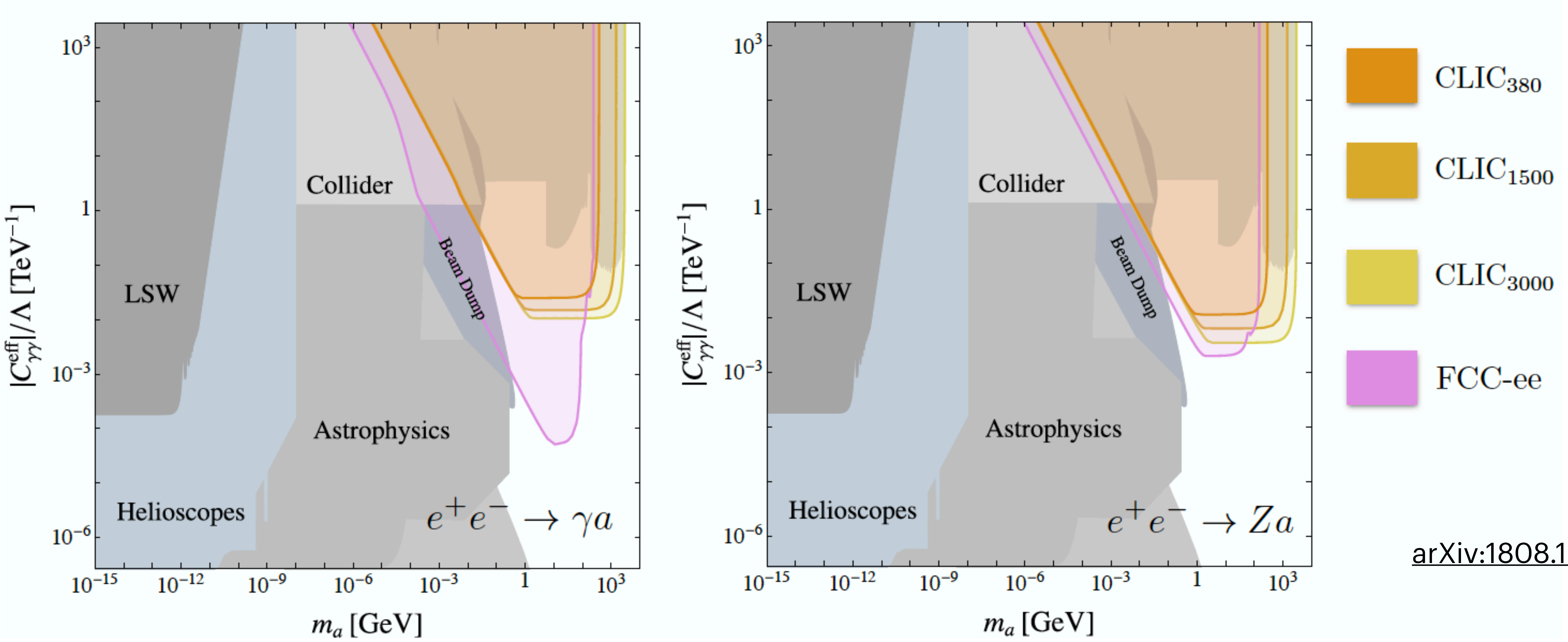


Regular matter
is very complex

ALPs

Axion-like particles

- Very-weakly-coupled window to the dark sector
- For small couplings and light ALPs, the ALP decay vertex can be considerably displaced from the production vertex → LLP

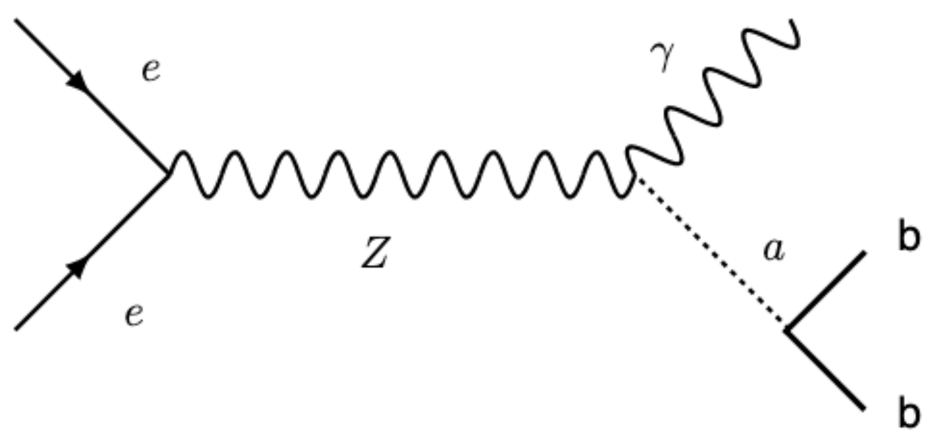


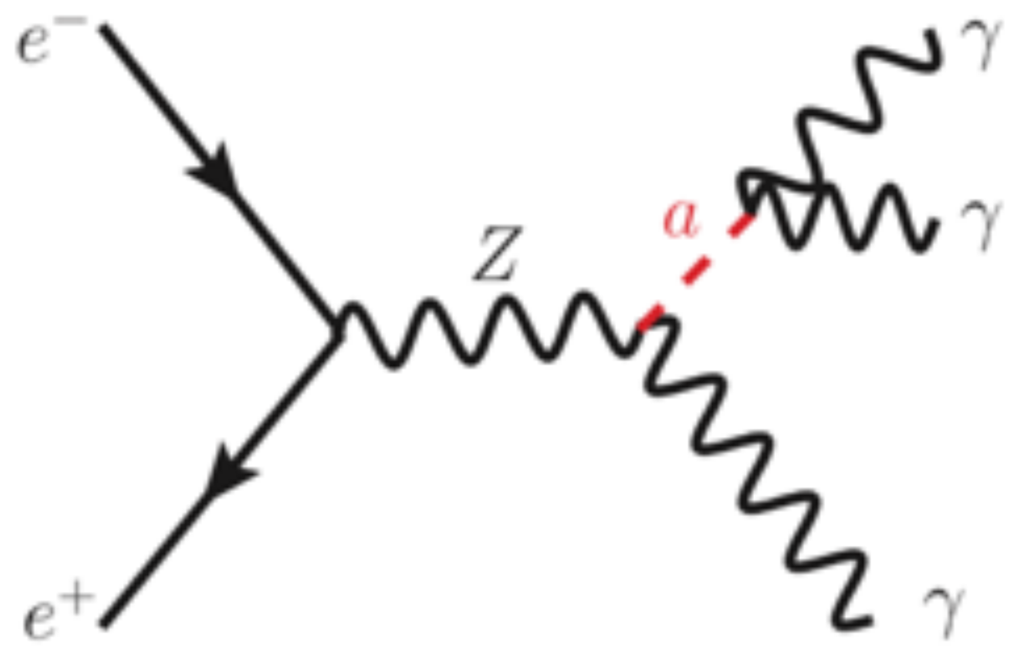
arXiv:1808.10323

FCC-ee: ALPs

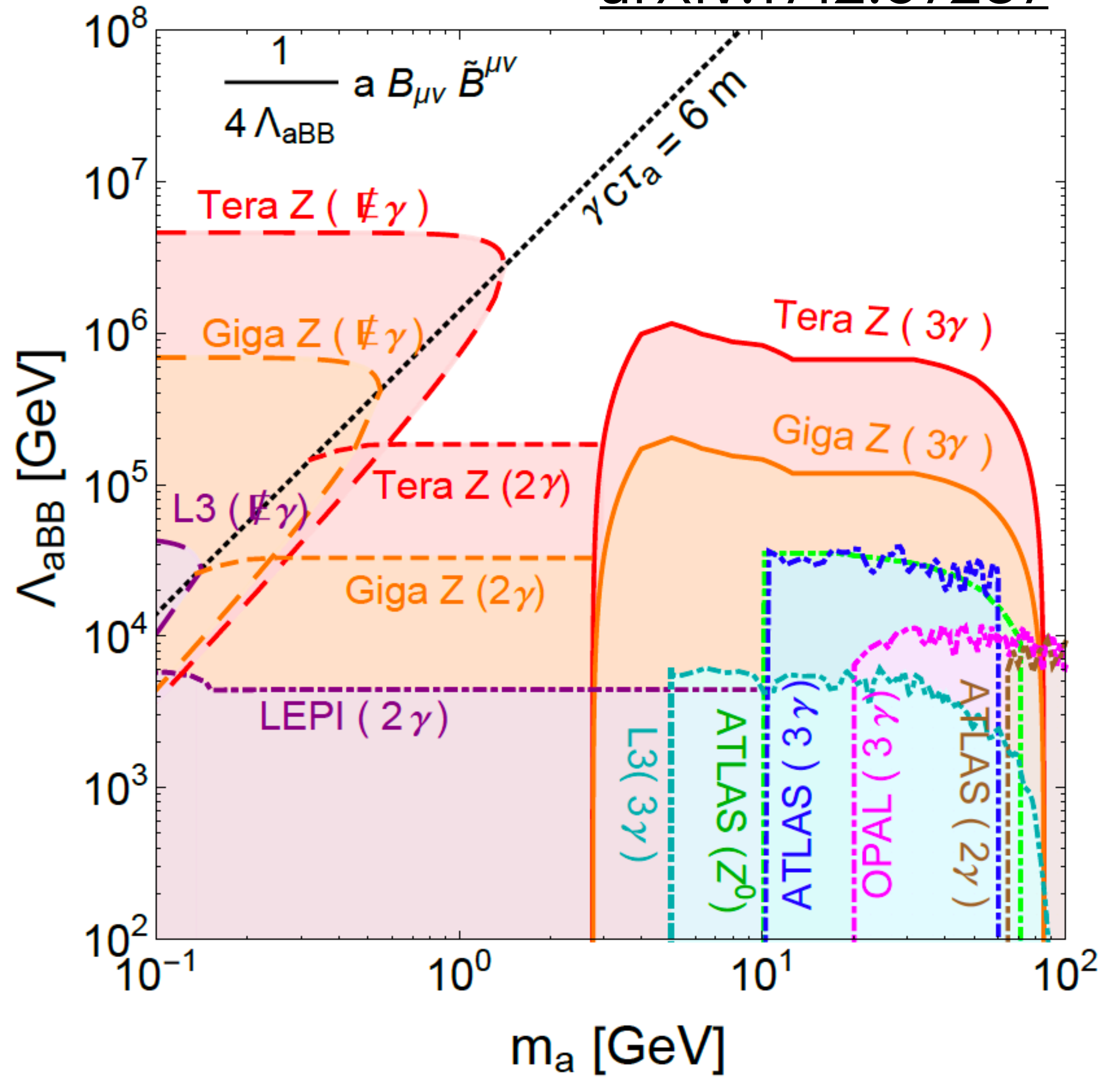
Produced with a photon

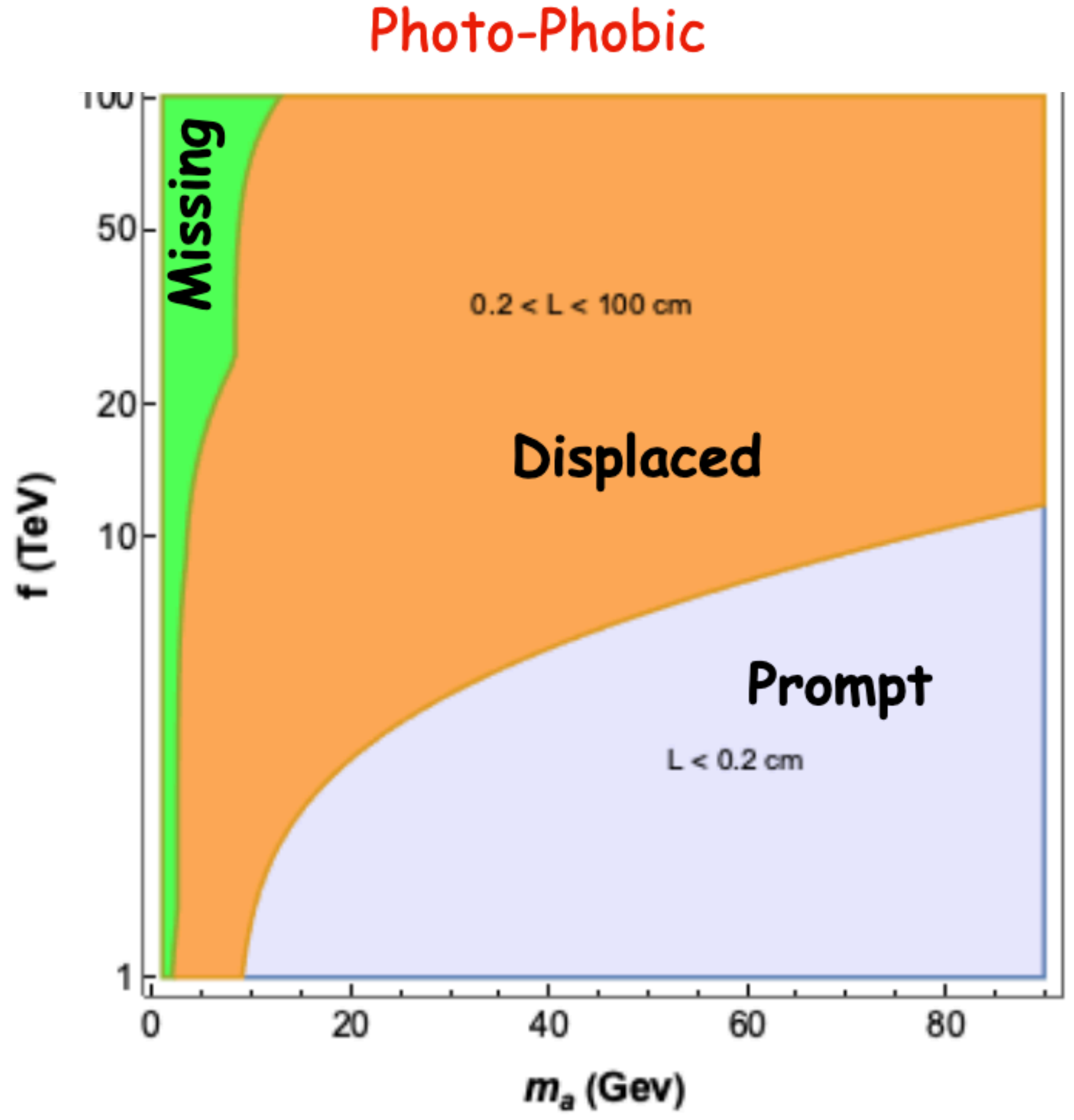
- Specially sensitive final states at the FCC-ee :
  - γ + MET for very light a
  - $\gamma\ \gamma$ for light a
  - $\gamma\ \gamma\ \gamma$ for heavier a
  - Orders of magnitude of parameter space accessible
- Recent paper **A. Iyer (June 2021)**
  - light (composite) axion-like particles
  - arXiv:2104.11064

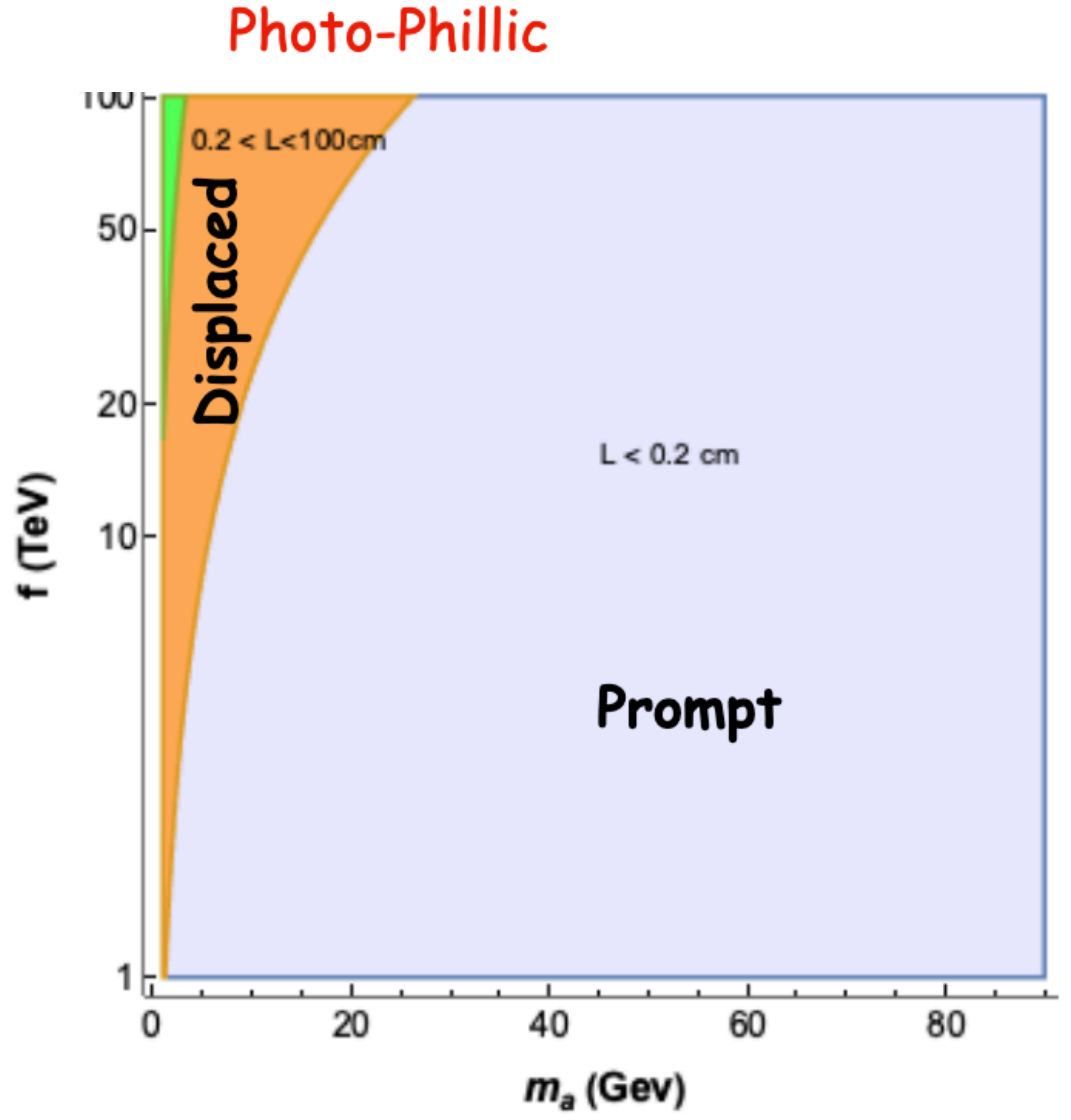




arXiv:1712.07237







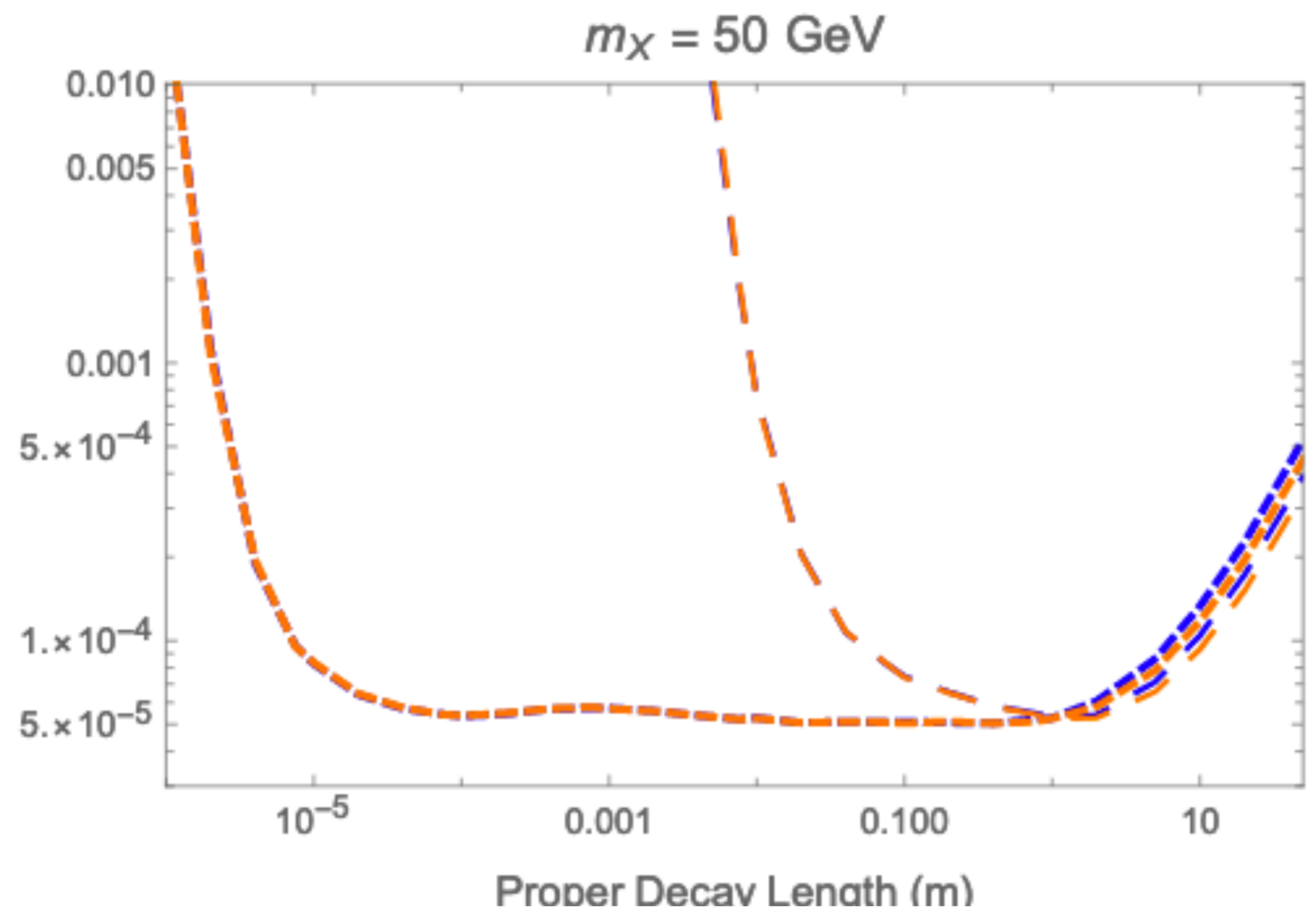
3. The Higgs boson

Exotic Higgs decays

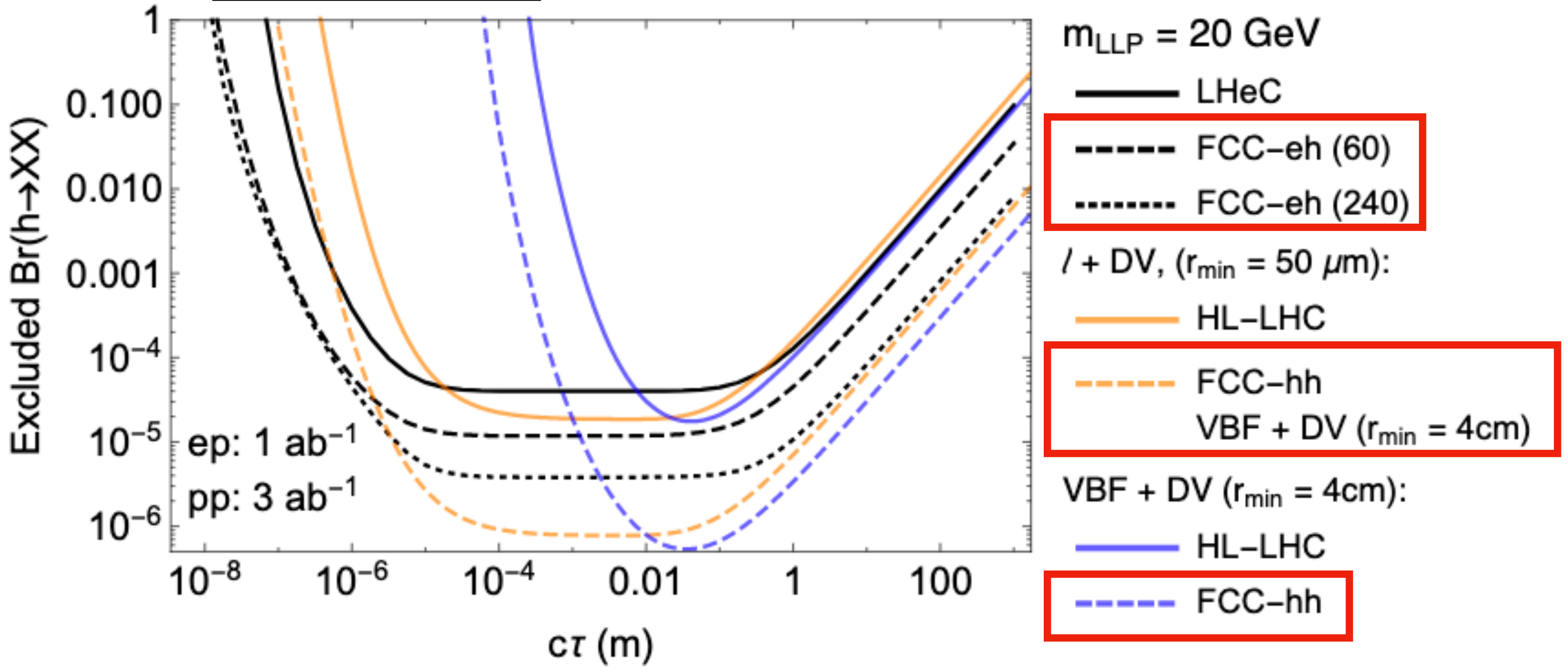
- The Higgs boson looks SM-like but it still could be exotic and provide us with indications of what lies beyond the SM

- Exotic Higgs decays to long-lived particles (LLPs) can be explored at future colliders
  - **Twin Higgs** models with displaced exotic Higgs boson decays, **Hidden Valley** models with neutral, long-lived particles that the Higgs boson can decay to (arXiv:1812.05588)
  - Long-lived particle signals arising from Higgsinos or exotic Higgs decays (arXiv:1712.07135)

FCC-ee. h→XX branching ratio limits as a function of decay length for an X mass of 50 GeV (more in ref). [arXiv:1812.05588]



arXiv:1712.07135



There is more

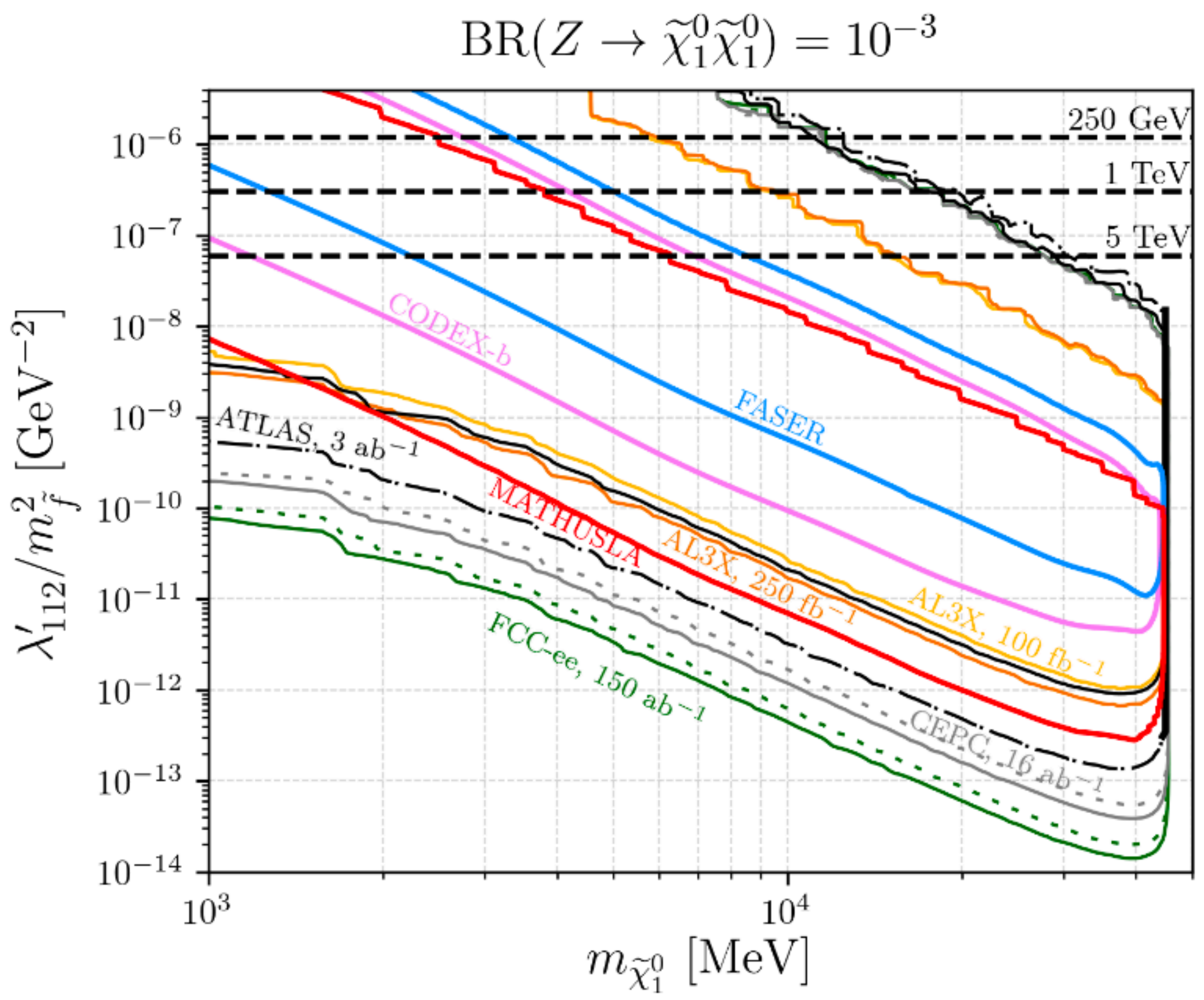
Mostly SUSY

- Finding valid motivations for LLP at the FCC is certainly not a problem
  - Higgs portal, dark glueball (arXiv:1911.08721)
  - Neutral naturalness (arXiv:1506.06141)
  - Folded SUSY (arXiv:1911.08721)
  - Neutralinos (arXiv:1904.10661)
  - Dark photon (arXiv:1909.02312)
  - Wino and higgsino dark matter with a disappearing track signatures (Eur.Phys.J C (2019) 79:469)

FCC-ee

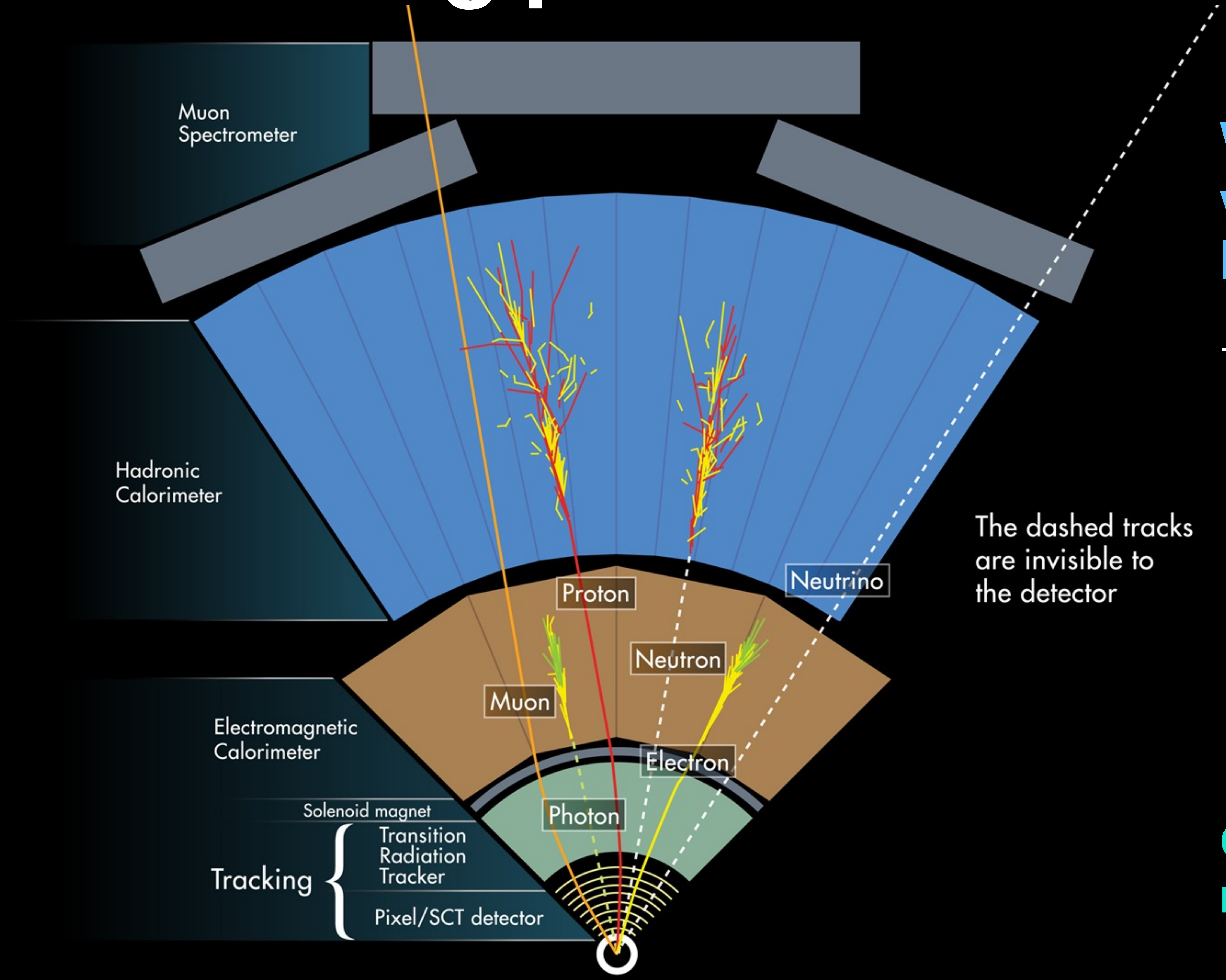
FCC-he

FCC-hh



arXiv:1904.10661

Detecting particles at colliders nowadays



We push the energy frontier → we produce heavier and heavier particles → short lived

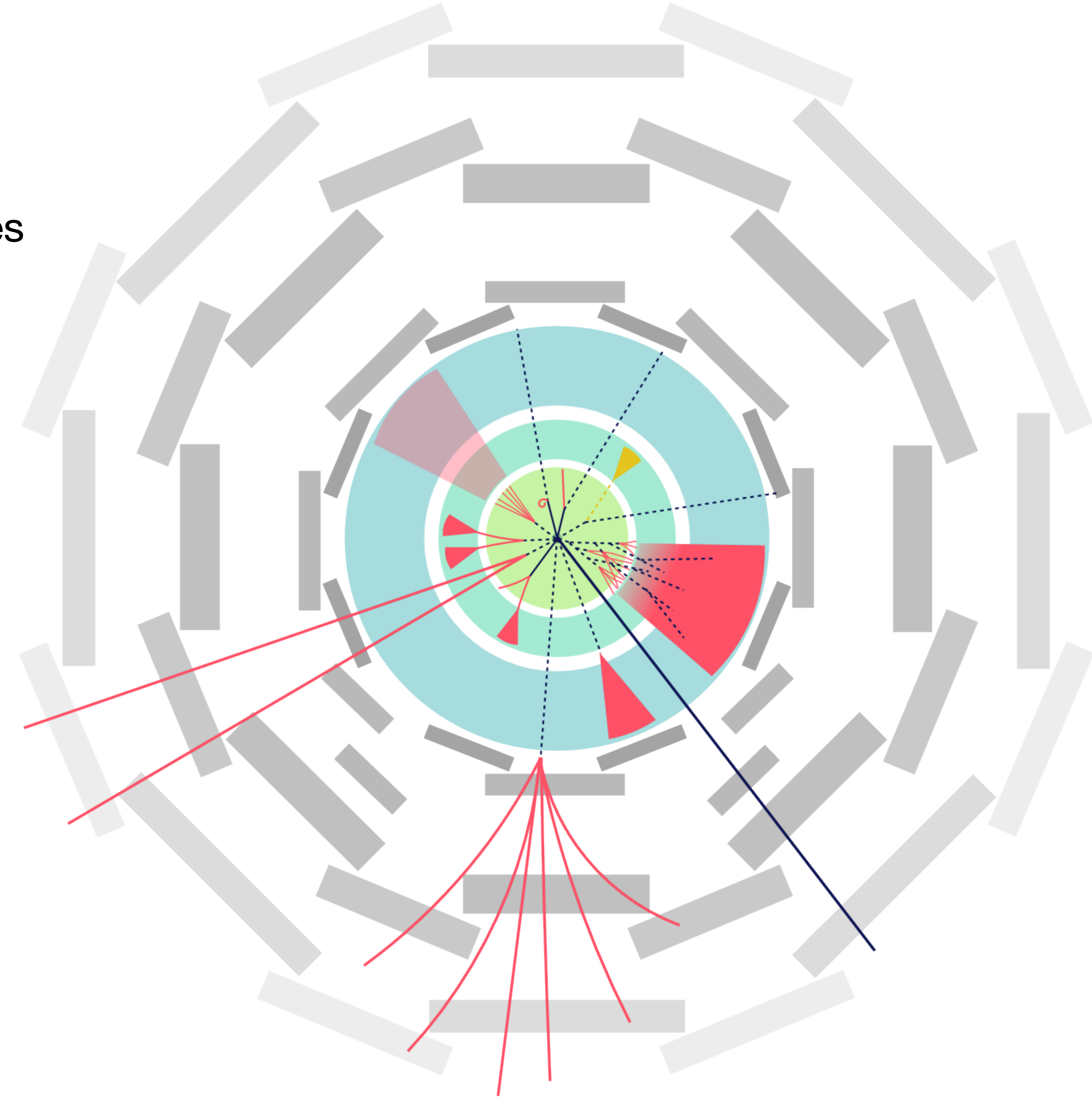
- The Higgs boson at the LHC:
  - A Higgs boson is produced and decays 10^{-22} seconds after
  - It often decays into two Z bosons, each of them decaying in about 10^{-25} s in e.g. a couple of muons each
  - In practice this means that we see 4 muons coming from the collision point

Our detectors, trigger, and reconstruction are made for that!

LLPs are not like that

They are weird

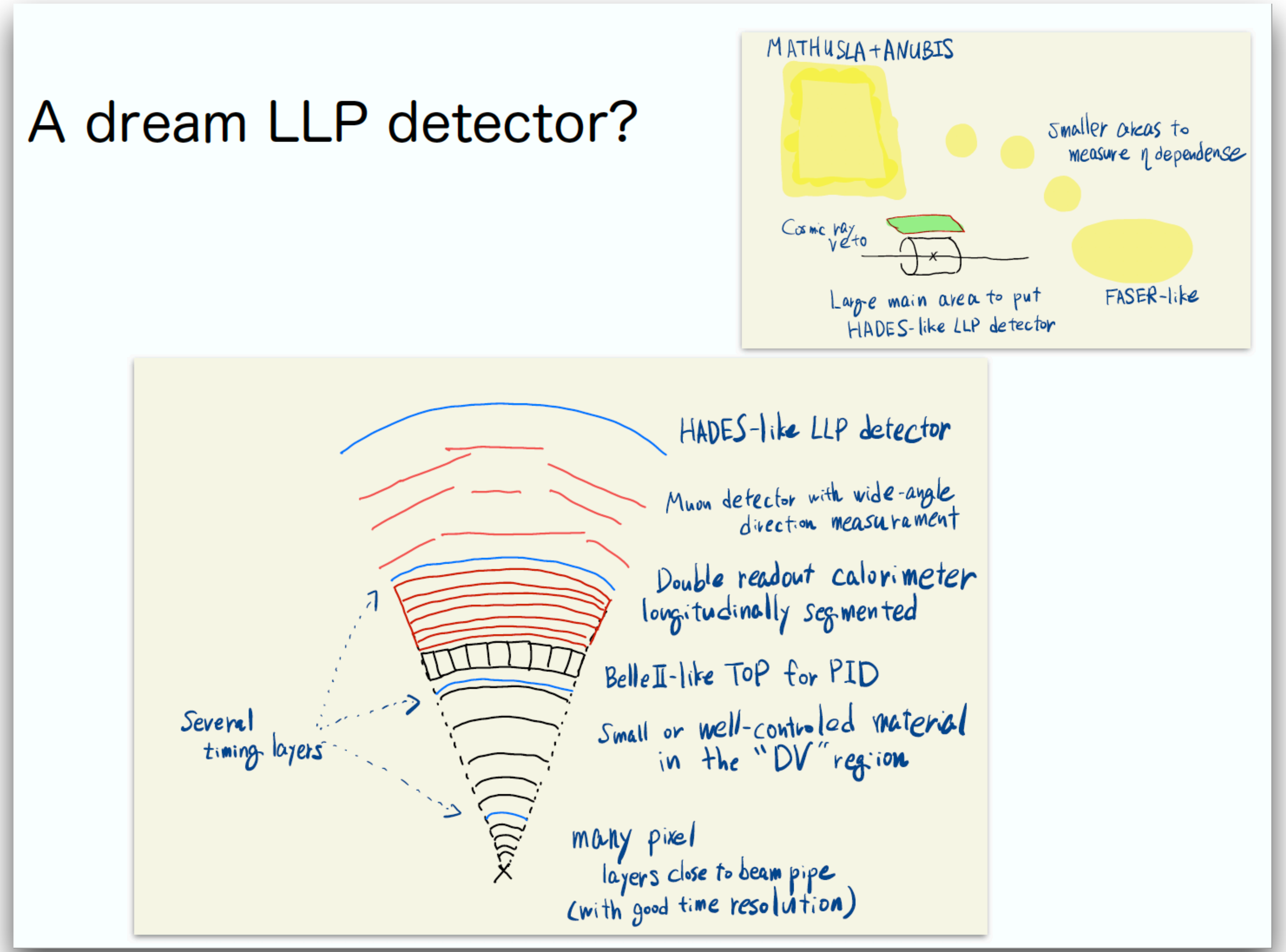
- New, long-lived particles display a collection of different signatures
  - Displaced tracks/vertices
  - Disappearing/kinded tracks
  - Anomalous tracks (dE/dX)
  - Slow/stopped particles (out of time)
  - Emerging signatures …
- Which means
  - Little/no backgrounds
    - Potential instrumental background (how to model?)
  - They need **Dedicated techniques**
    - Reconstruction, Trigger, and Detector Design



https://hrussell.web.cern.ch/

This won’t be different at the FCC

Unless we do something about it



It is a good time to plan our ***dream LLP detectors***, following Ryu Sawada first example at the latest LLP workshop in November (link)

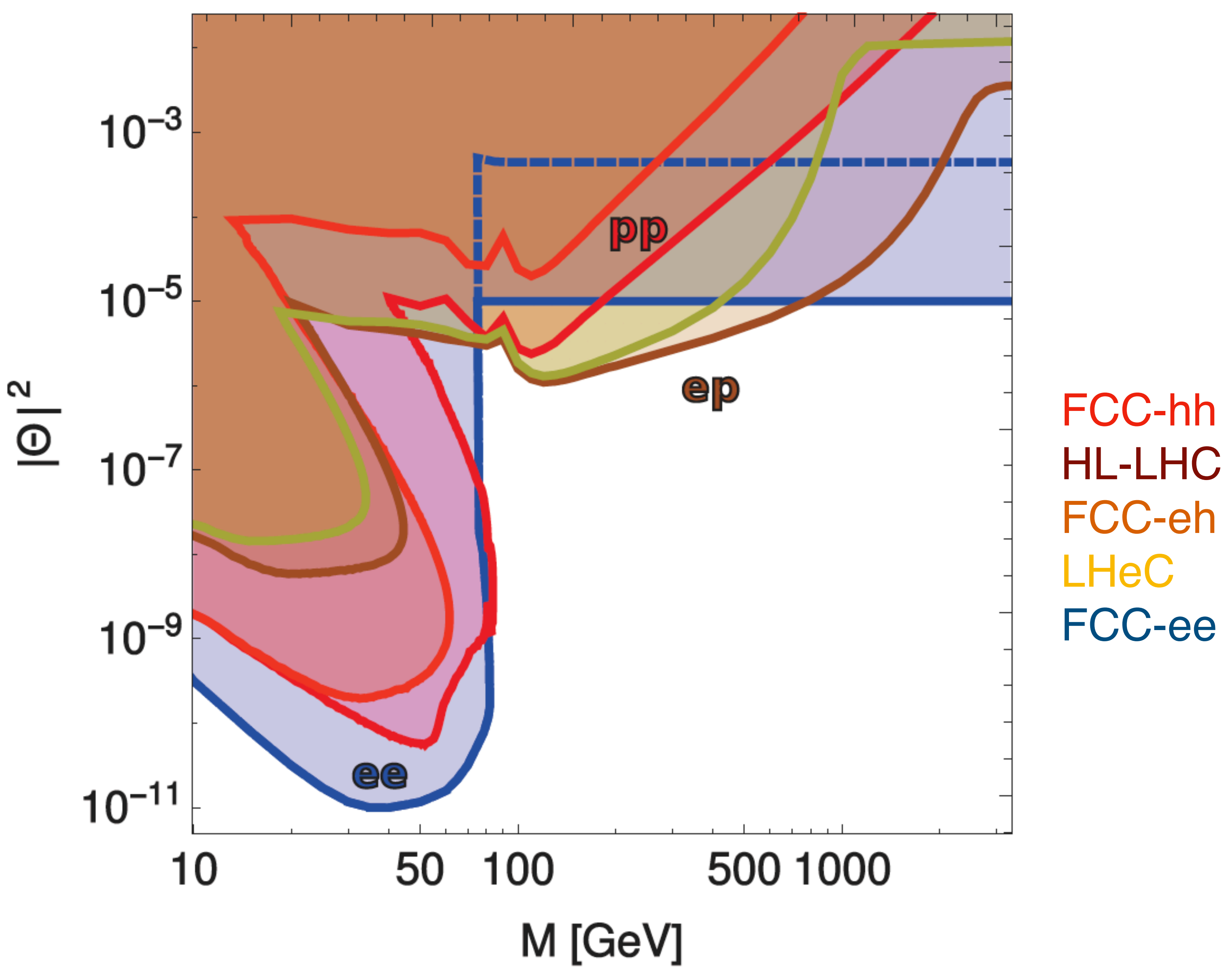
- At this point we have two ways to go:
  - Design the future detectors as usual and then try to make the best out of them for LLPs
    - which can be done but won’t be easy as we know from the experience at the LHC -and before-
  - Design the future detectors with LLP in mind, prioritising for example displaced tracking and timing, and budgeting for unexpected signals
    - which can bring up not only a boost for these searches but also **innovation**

Complementarity

HNL is a good example

- The complementarity of the three different stages of the FCC provides unique potential to discover and pin down these particles

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

Summary and next steps

- LLP searches are an attractive alternative (and complement) to mainstream new physics searches
  - But challenge conventional reconstruction and trigger methods
- Many interesting lines to explore: Heavy Neutral Leptons, Hidden sectors, exotic Higgs decays…
  - The FCC will have observation potential
  - The different phases will allow for proper characterization of any observation
  - **Work was kickstarted within the FCC-ee with an Snowmass LoI, now a case study (http://cern.ch/go/QT86)**
- LLP studies at the FCC offer many opportunities: Detector design, Reconstruction algorithms, Trigger
- Given the breadth of LLPs, it is worth to keep an open conversation beyond collider physics
  - To tell a coherent story and to put limits and observations in context
- 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/
  - We could follow a similar approach