Searches for LLPs at

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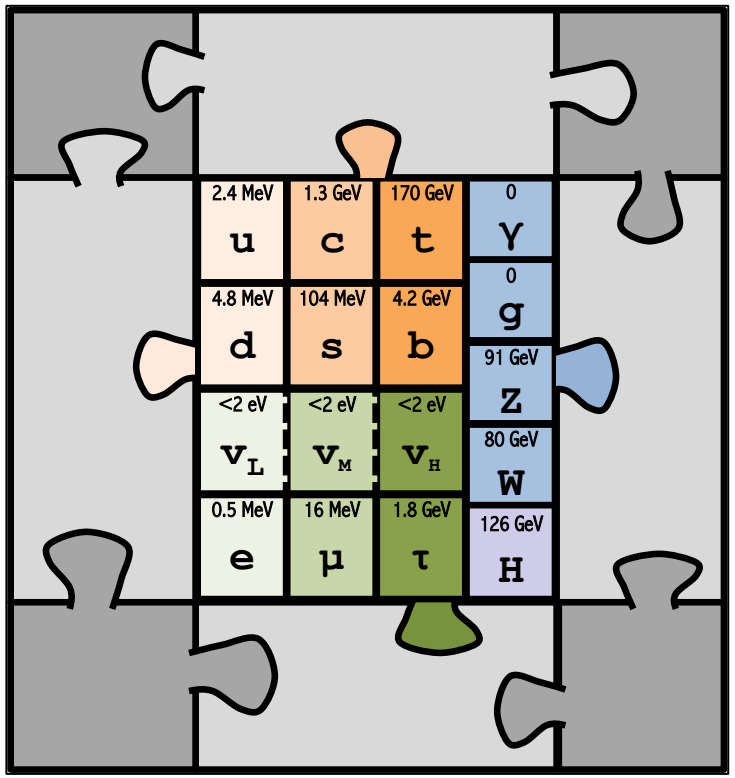
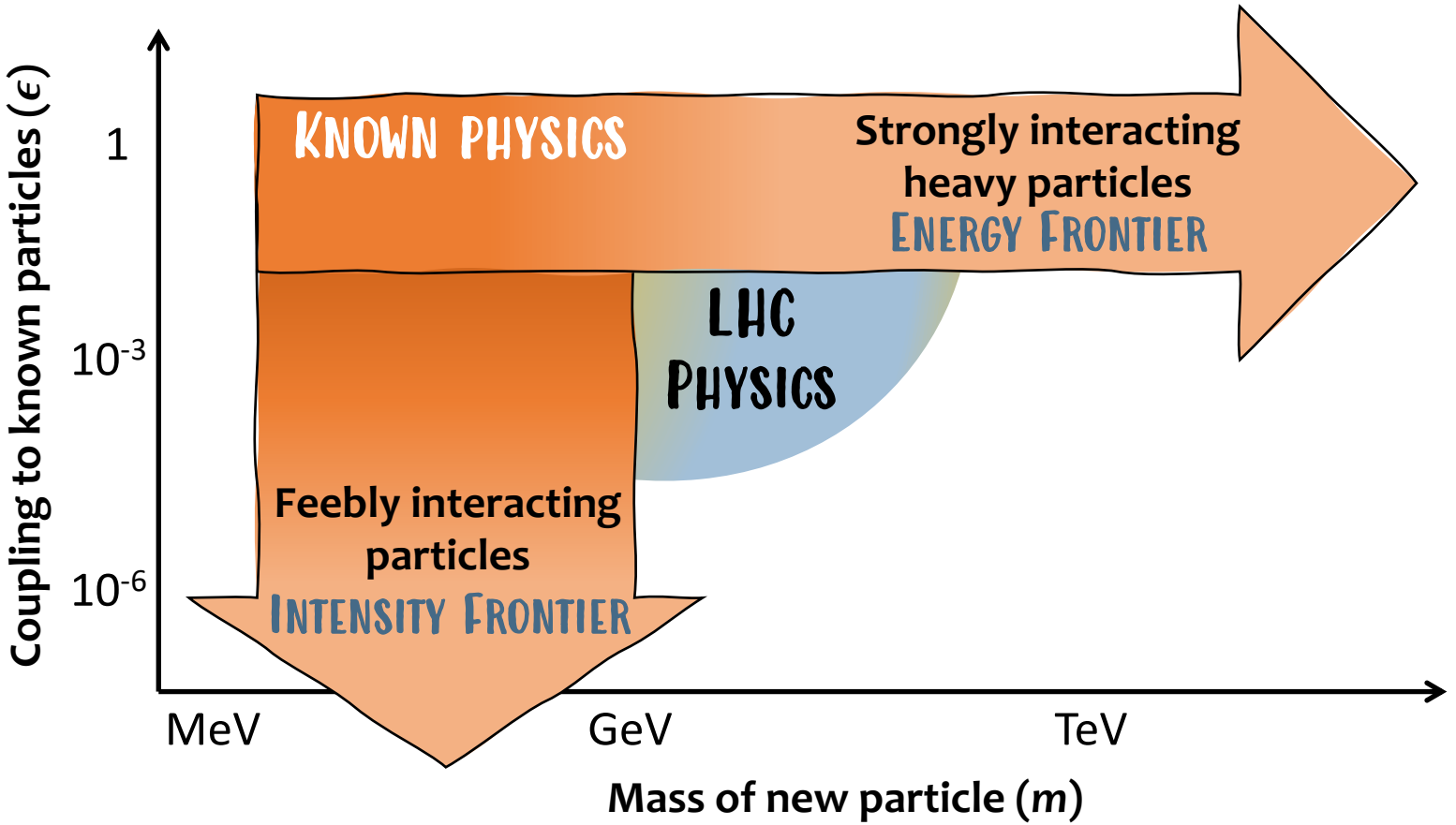
The landscape of new particles @ colliders

- Collider physics: a plethora of measurements and searches
- The Standard Model is complete and confirmed. Burning questions remain!





Feebly Interacting Particles (FIPs)

- Due to interacting feebly, they are linked to a “hidden sector”
- Couplings between SM and hidden sector result from “portal” operators
- Large number of specific models; can be simplified to the following:

SM Higgs *h* — h ----- $(\mu S + \lambda S^2) H^\dagger H$ ----- S — Dark Higgs *S*

New scalar: **Dark Higgs**; couplings to SM μ, λ

SM EM *A* — A ~~~ $-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} F_Y^{\mu\nu}$ ~~~ A_D — Dark EM A_D

New vector: **Dark photon**; coupling to SM $\propto \epsilon Q$

SM 2γ or $2f$ — 2γ --- $\frac{\alpha}{f_\alpha} F_{\mu\nu} \tilde{F}^{\mu\nu}$; $2f$ ---- $\frac{\partial_\mu \alpha}{f_\alpha} \bar{\psi} \gamma^\mu \gamma^5 \psi$ ----- α — ALP α

New pseudo-scalar: **ALP**; coupling to SM suppressed

(Axion Like Particle)

SM LH ν — ν — $y_N h L \psi_D$ — N — HNL *N*

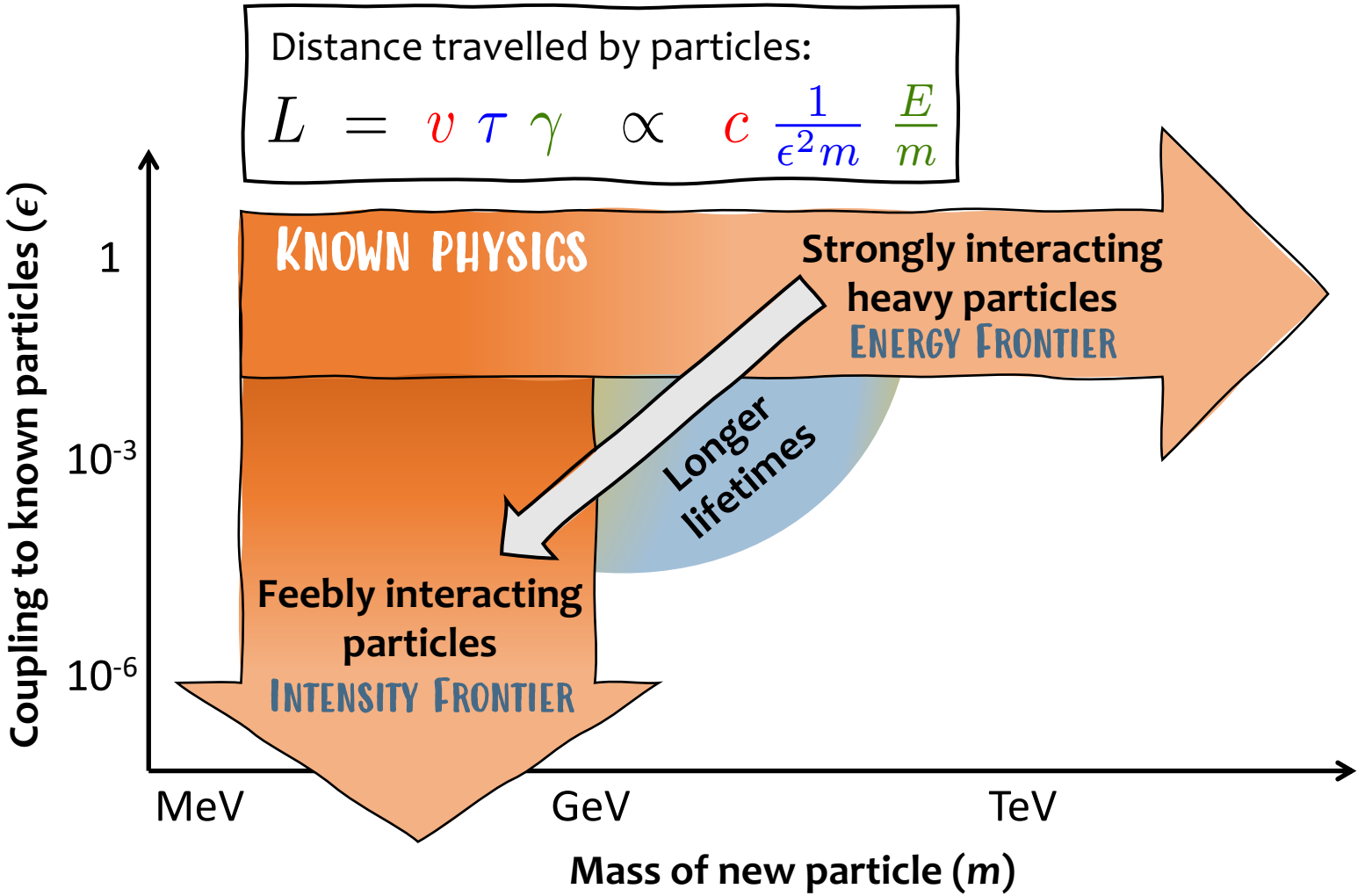
New fermion: **HNL**; coupling to LH SM and h $\propto y_N$

(Heavy Neutral Lepton)

- The masses of the new particles can span several orders of magnitude

The landscape of new particles @ colliders

- **Lifetime:** a characteristic of weakly interacting (light) particles
- Distinct signatures
- **Opportunity for exploration!**
  - in current and **future colliders** and dedicated experiments



Why is the FCCee relevant for these?

TERA-Z RUN

Stage	Collisions	CME	L (ab^{-1})	N events
FCC-ee	e^+e^-	90 GeV (Z-pole)	150	**$5x10^{12}$** Z
		160 GeV (WW)	10	10^8 WW
		240 GeV (HZ)	5	10^6 HZ
		365 GeV (tt)	1.5	10^6 tt
FCC-hh	pp	100 TeV	30	$2x10^{10}$ H $3x10^7$ HH
FCC-eh	ep	3.5 TeV		

Runs with heavy ions not included

Towards assessing sensitivity to FIPs

Opportunities for detailed studies

European strategy update
(2018-2020)

European Strategy Update

Snowmass community planning
(2020-2022)

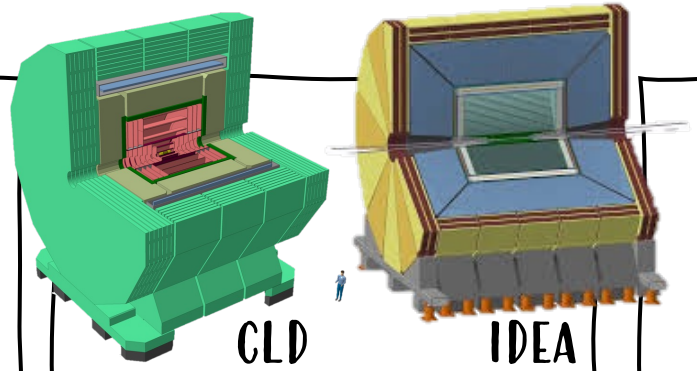
Snowmass 2021

FCC feasibility study
(input to next stategy update)

FCC

Typical workflow

Sample generation of various models, e.g.
MadGraph5_aMC@NLO for parton-level e^+e^-
PYTHIA for parton shower and hadronisation



Parameterised detector simulation
e.g. IDEA DELPHES card

Analysis code
e.g. FCCAnalysis

Towards assessing sensitivity to FIPs – 2

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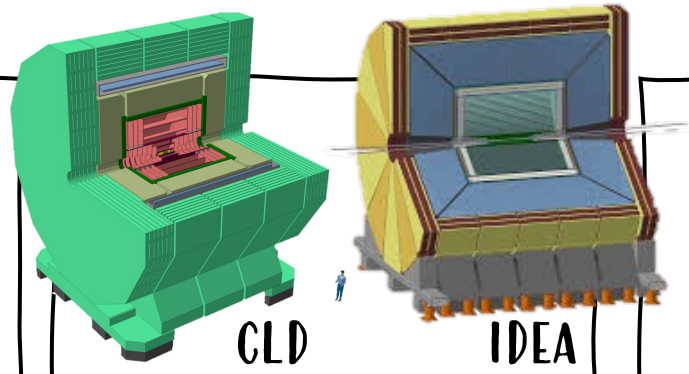


Parameterised detector simulation
e.g. IDEA DELPHES card

Analysis code
e.g. FCCAnalysis

FCC SW: https://hep-fcc.github.io/FCCeePhysicsPerformance

Within FCCAnalysis

Analysis Framework
Identify objects and relevant quantities
e.g. electrons, muons and jets

Event selections
Apply analysis cuts
e.g. lepton multiplicity

Plotting
Make final plots

Examples: https://github.com/HEP-FCC/FCCeePhysicsPerformance/tree/master/case-studies/BSM/LLP

One example!
See backup for more

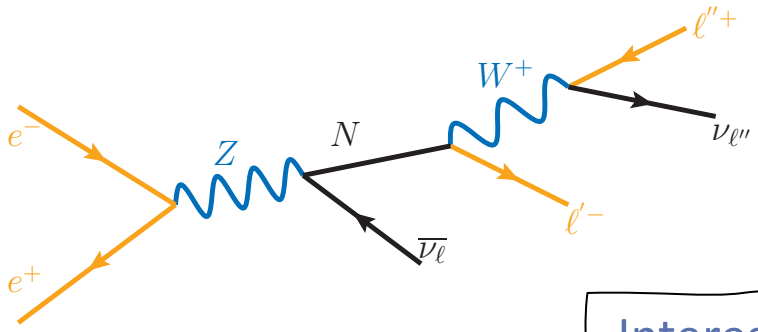
Neutrino Portal – HNLs

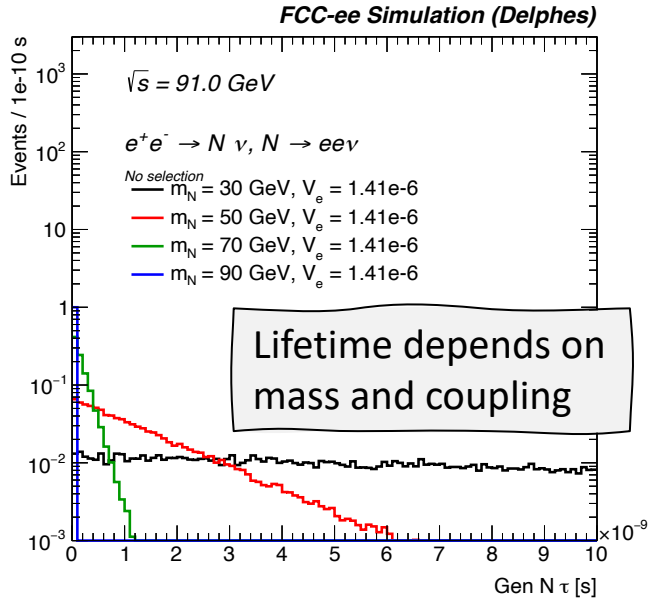
Many theoretical puzzles associated with neutrinos

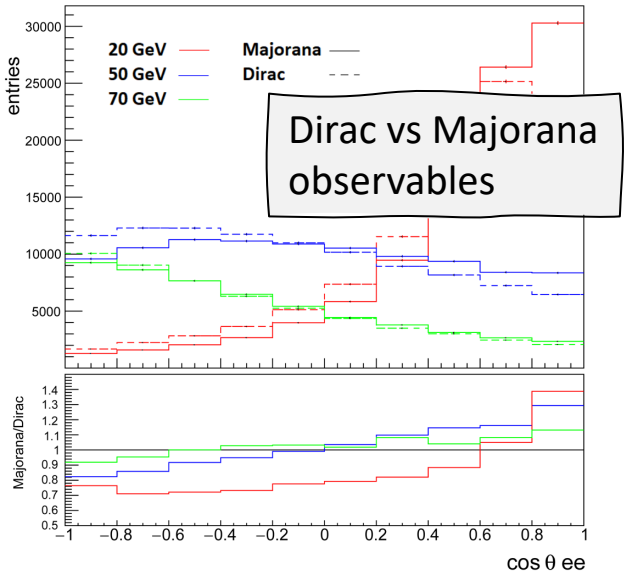
- Oscillations, masses, further properties
  - e.g. Dirac or Majorana?

See-saw mechanism

- Generic model used to understand the relative sizes of observed neutrino masses to other fermions
- Two or more right-handed fields
- Results in new particles: Heavy Neutral Leptons (HNLs)
- Do these particles exist? What are their masses?
- Are they Diract or Majorana?
- $\mathcal{L}^{int} = \mathcal{L}^{W} + \mathcal{L}^{Z} + \mathcal{L}^{H}$





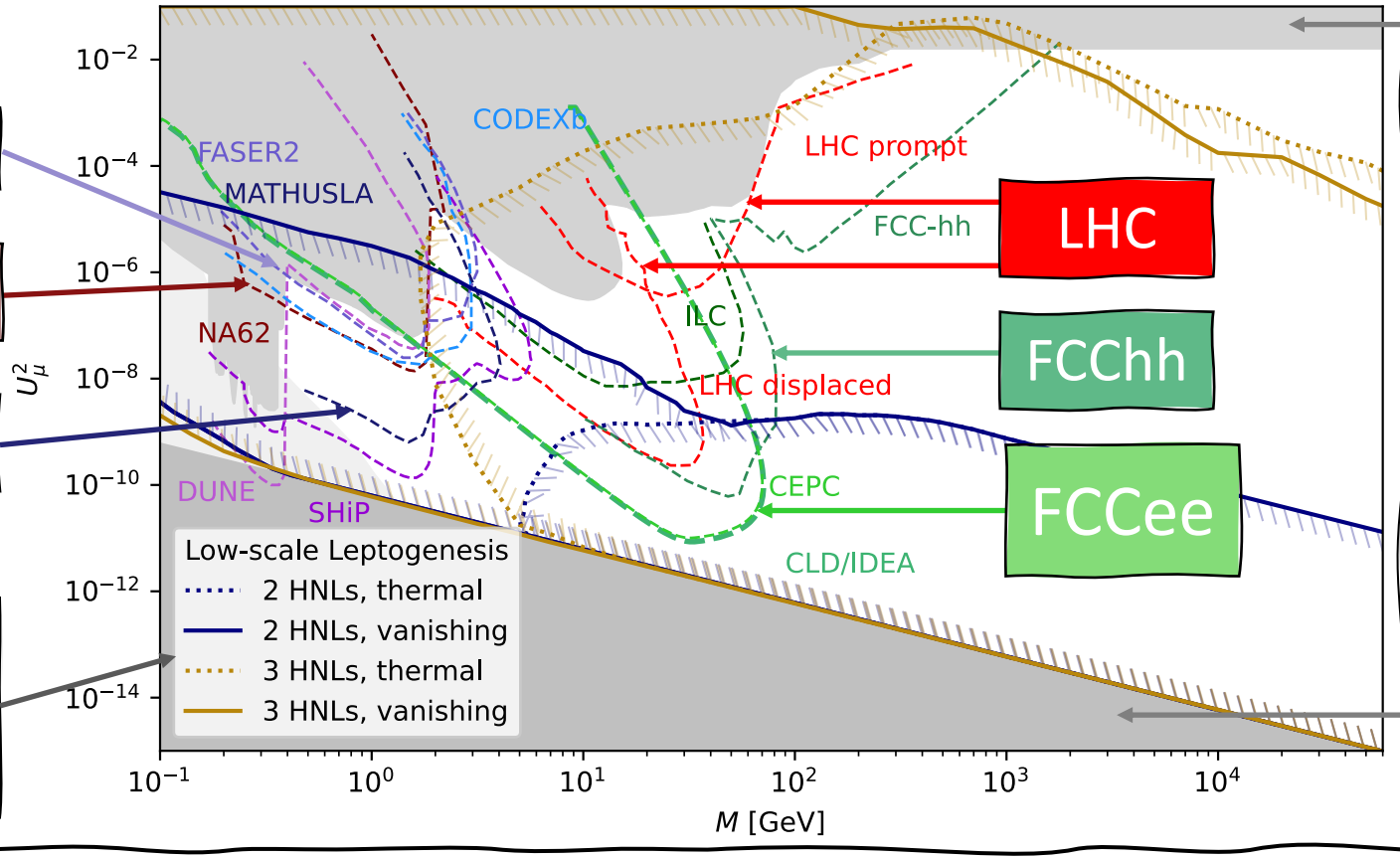


Interesting experimental explorations ahead

LLPs at FCC – 2203.05502

One example!
See backup for more

Reach for HNLs in future experiments



FASER2

NA62

MATHUSLA

Different initial conditions in early universe

Constrains from past experiments

LHC

FCChh

FCCee

Lower bound from the requirement to explain light neutrino oscillation data

FCC-ee running at the Z-pole has the potential to exclude the region of masses and couplings down to the see-saw limit

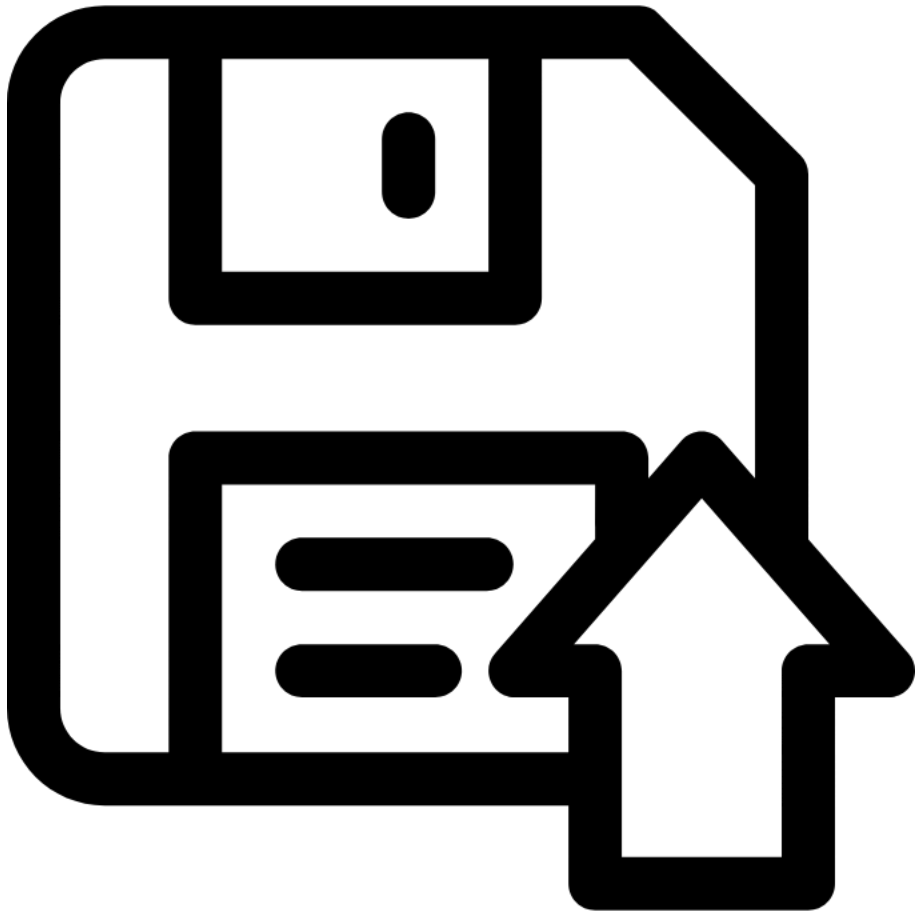
LLPs at FCC – 2203.05502

In brief

- FCCee will push the intensity frontier of particle physics
  - 5×10^{12} Z bosons expected to be produced
- It has the potential to discover **feebly interacting new particles**, in a phase space where no other experiment will ever have sensitivity
  - HNLs, dark Higgses, ALPs, dark photons
- **Unique opportunity to help answer some of the pressing questions of our Universe**
- We need to study FIPs@FCC now, to account for them in the design of the detectors and facilities
- Lots of room for newcomers – please join the pursuit!

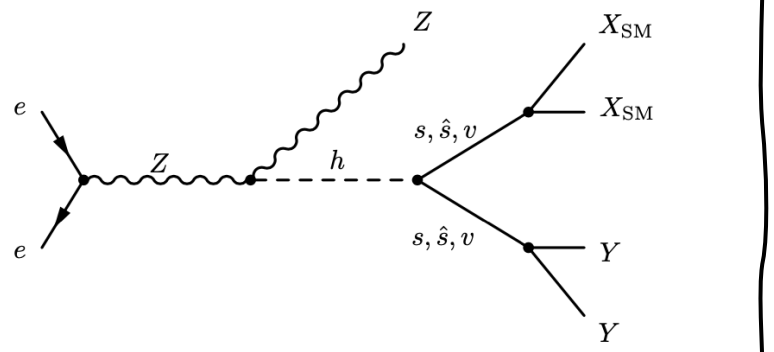
LLP-FCCee-informal@cern.ch

https://indico.cern.ch/category/5664/



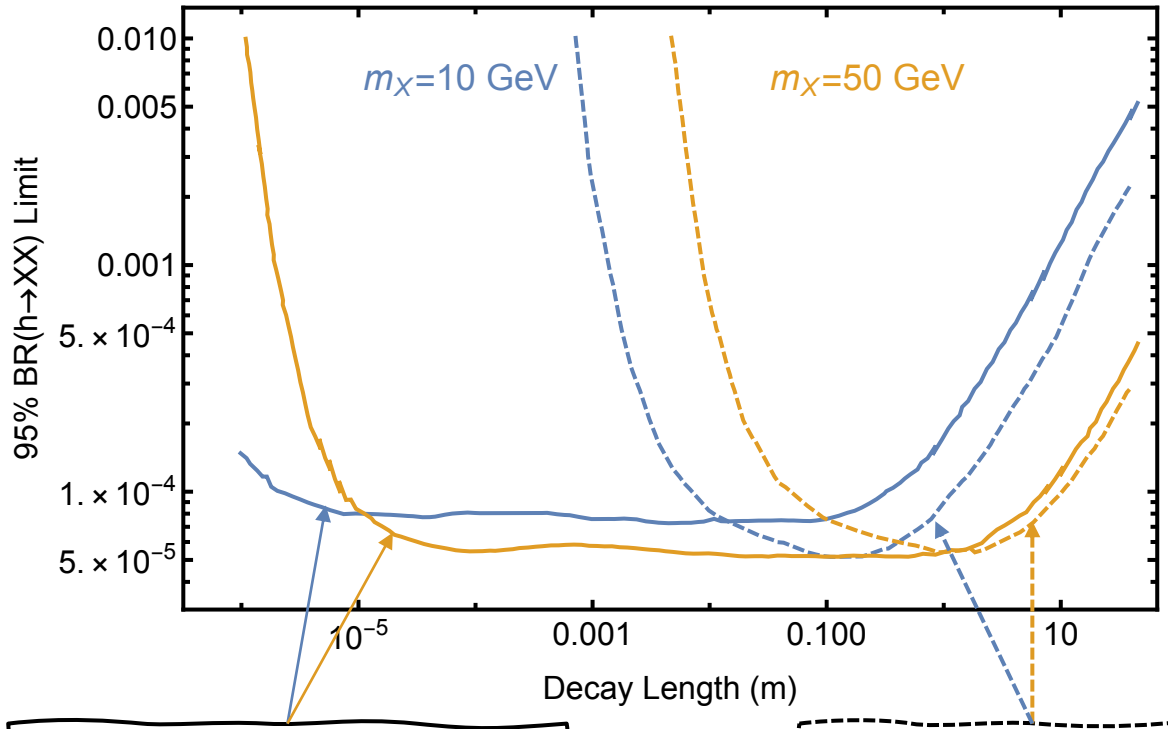
Exotic decays of the Higgs Boson

- The only elementary scalar particle that has been discovered!
  - Can have sizeable coupling to undiscovered particles
  - "Put it under microscope, study it to death" – N. Arkani-Hamed



Example production of LLPs through exotic decays of the Higgs boson *h* to scalars *s*, pseudo-scalars $\hat{s}$, or vectors *v*

Sensitivity of FCCee to exotic Higgs boson decays to LLPs (X)

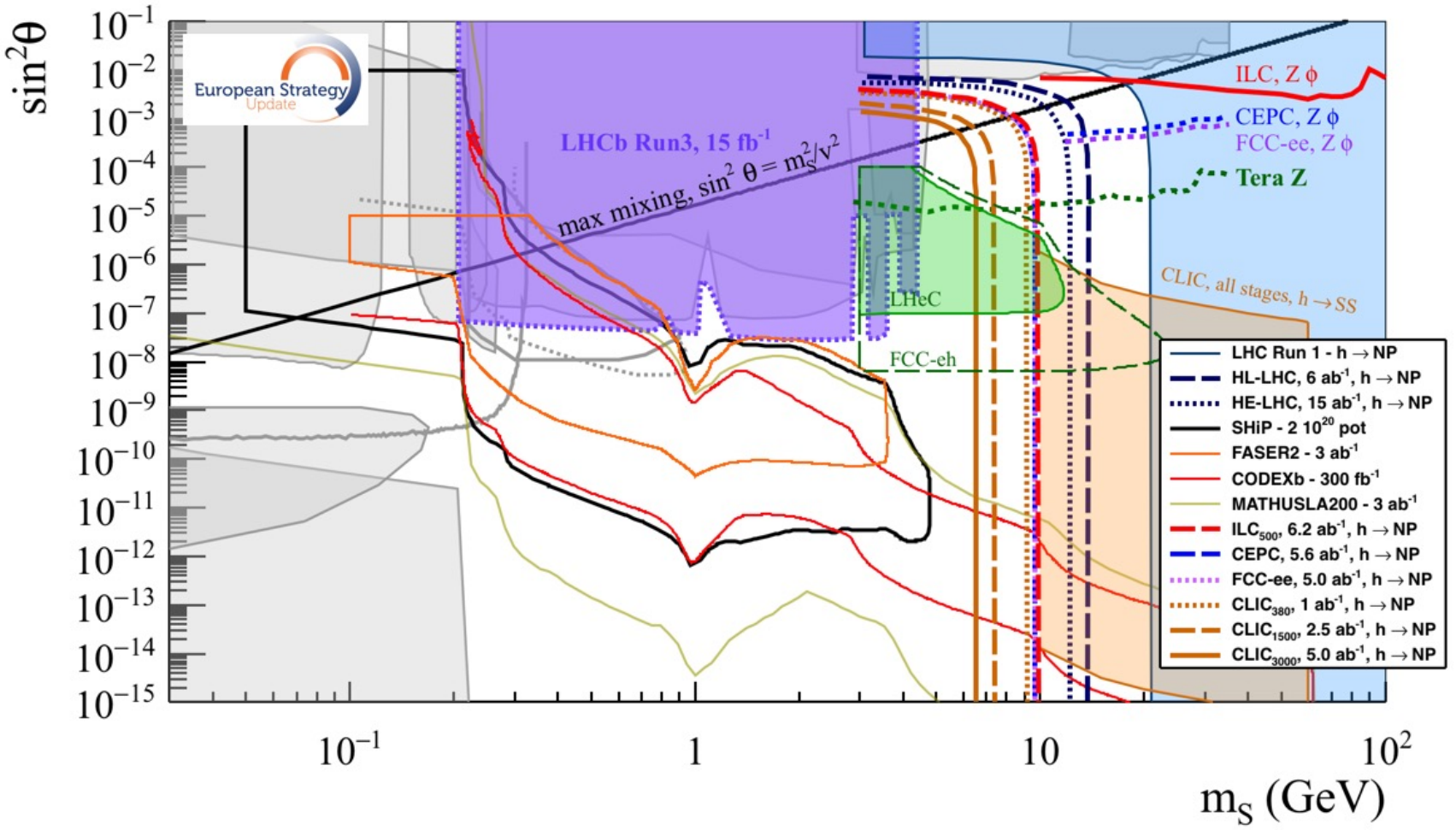


Invariant mass cut to retain sensitivity to shorter decay lengths

Cuts optimised for longer decay lengths

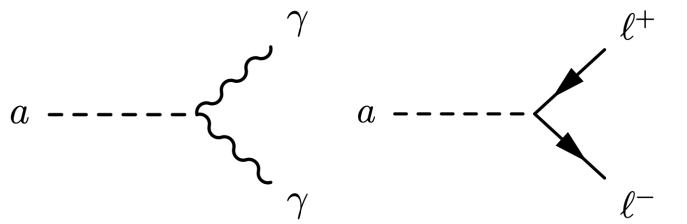
Recent review – input to Snowmass – arXiv:2203.06520

Reach for Dark Higgs

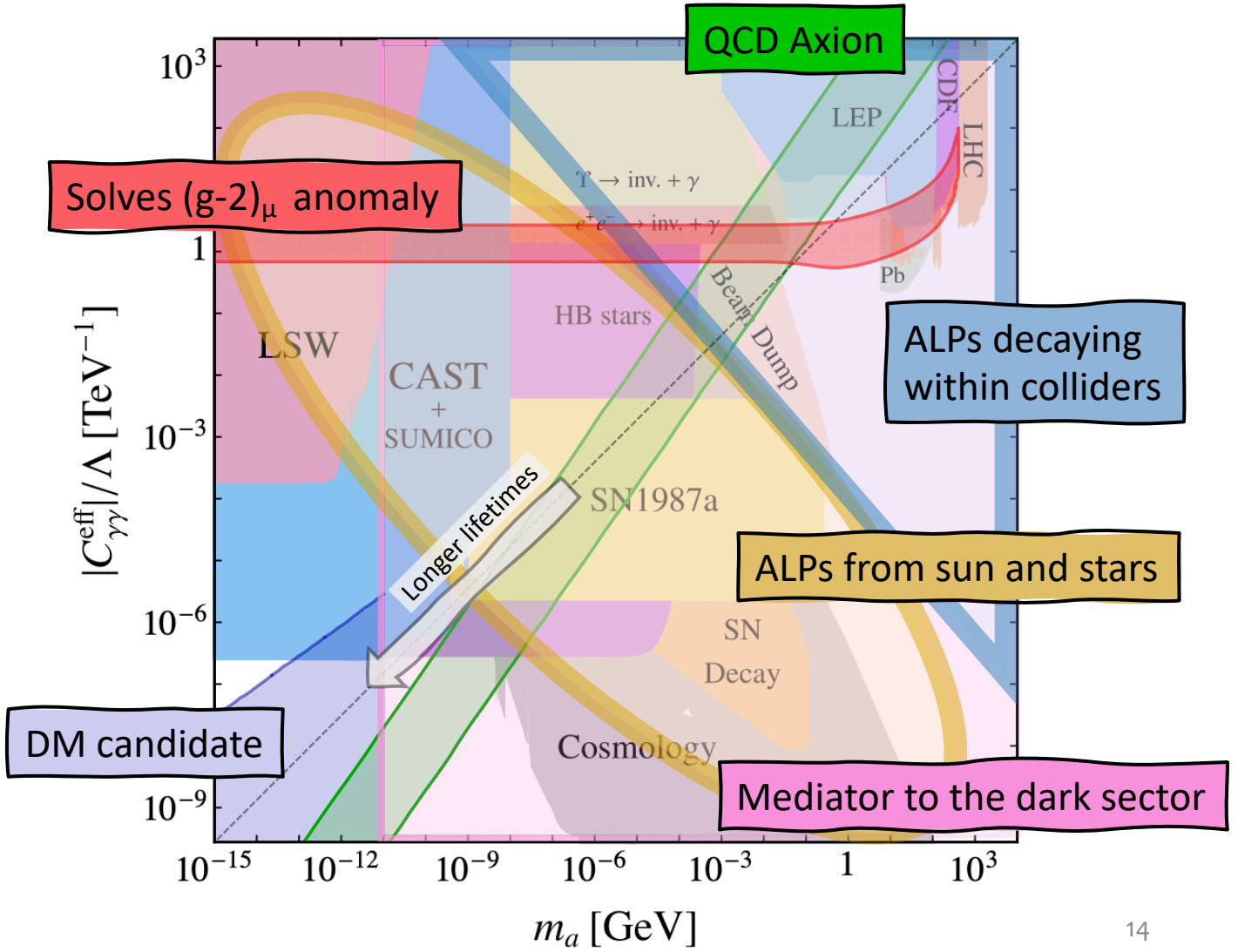


Pseudoscalar portal – ALPs

- Pseudoscalar SM-singlets; can appear in theories with broken global symmetries
- "Low" mass particles with suppressed couplings to SM
- BR to SM particles depends on their mass

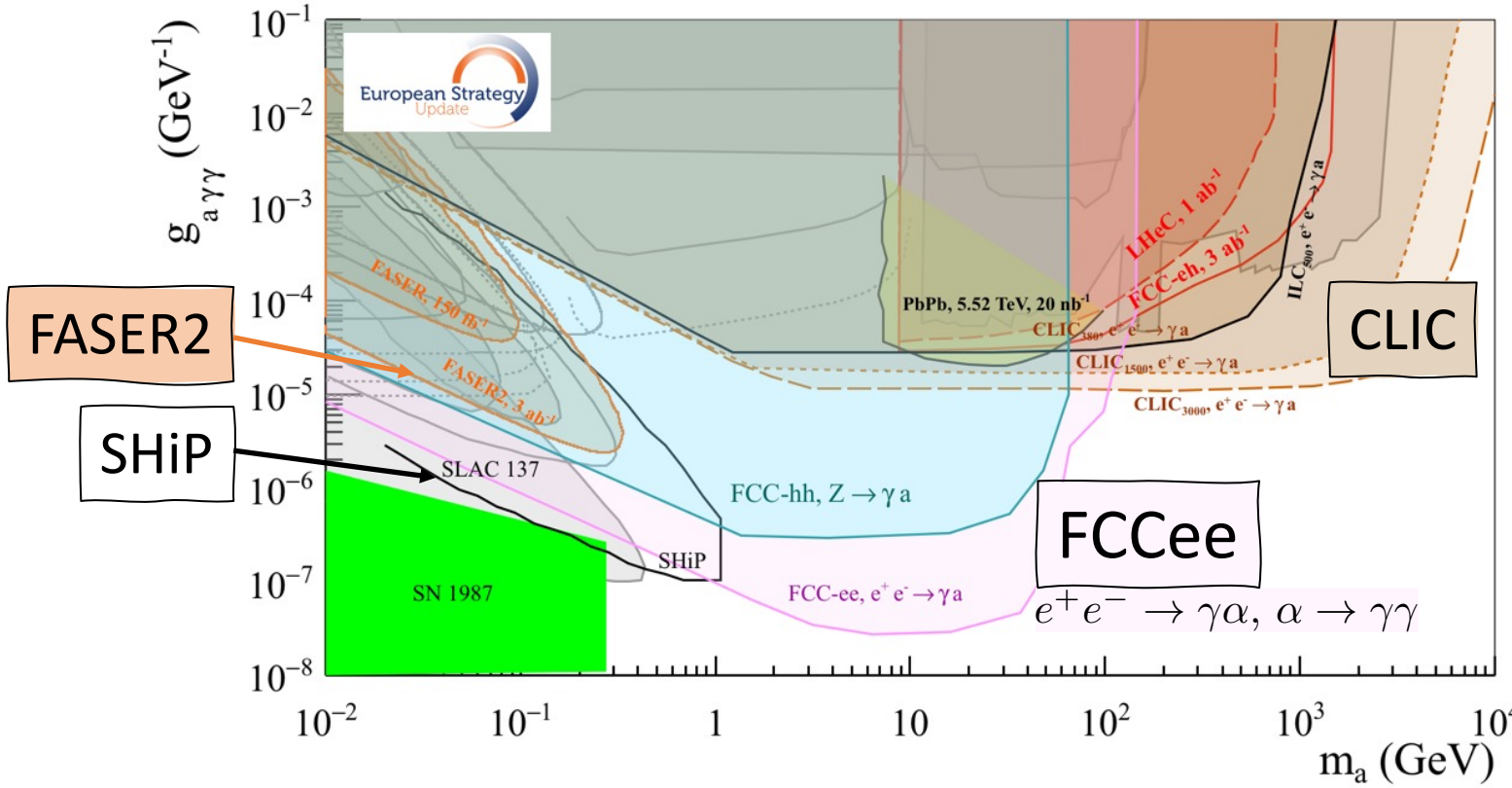


Dominant decays at the FCC



Thanks to Andrea Thamm for the figure!

Reach for ALPs in future experiments

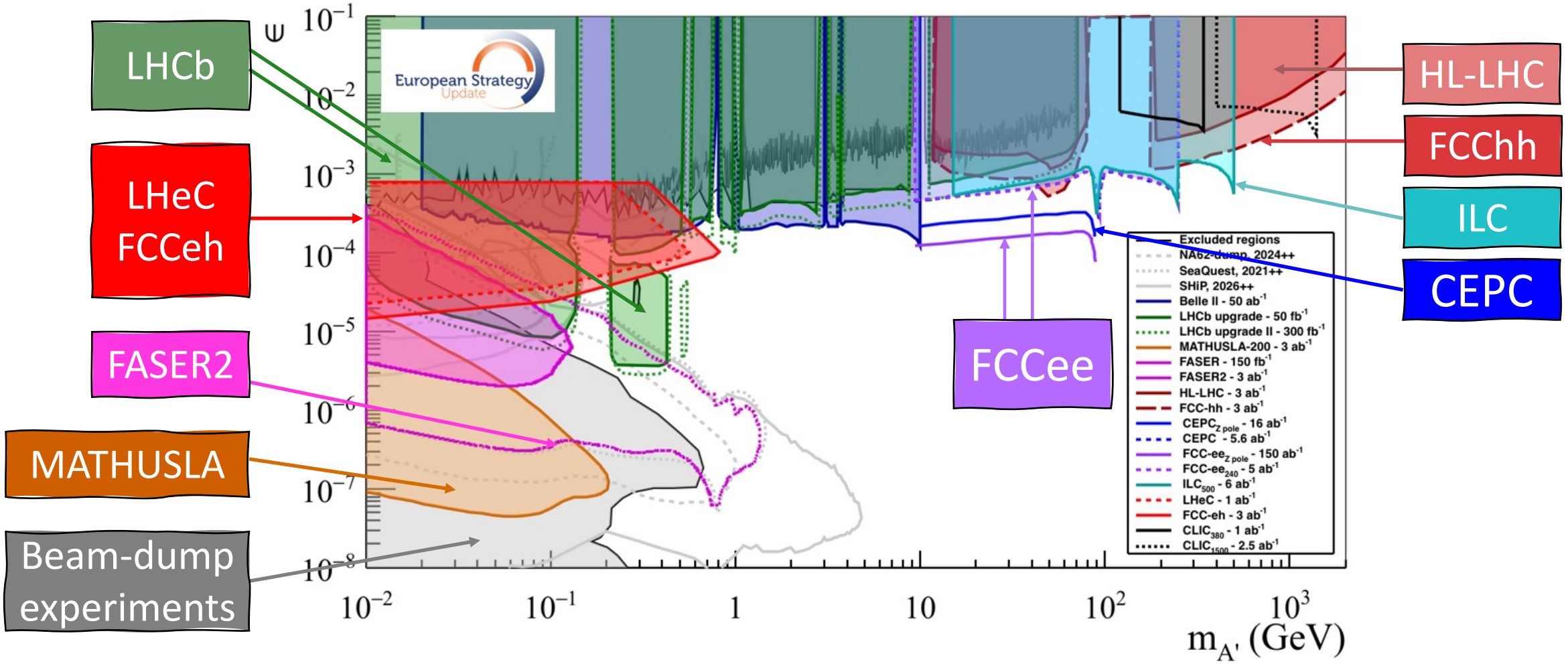


- Couplings to H accessible via $e^+e^- \to H\alpha,\ \alpha \to b\bar{b}$
  - similar for couplings to Z
- Decays to SM particles other than photons are less constrained
  - additional opportunity for ALP discovery at the FCCee.

The sensitivity provided by FCCee uniquely extends other limits by up to four orders of magnitude in the 1-100 GeV mass range

Recent review – input to Snowmass – arXiv:2203.06520

Vector portal – Reach for dark photons



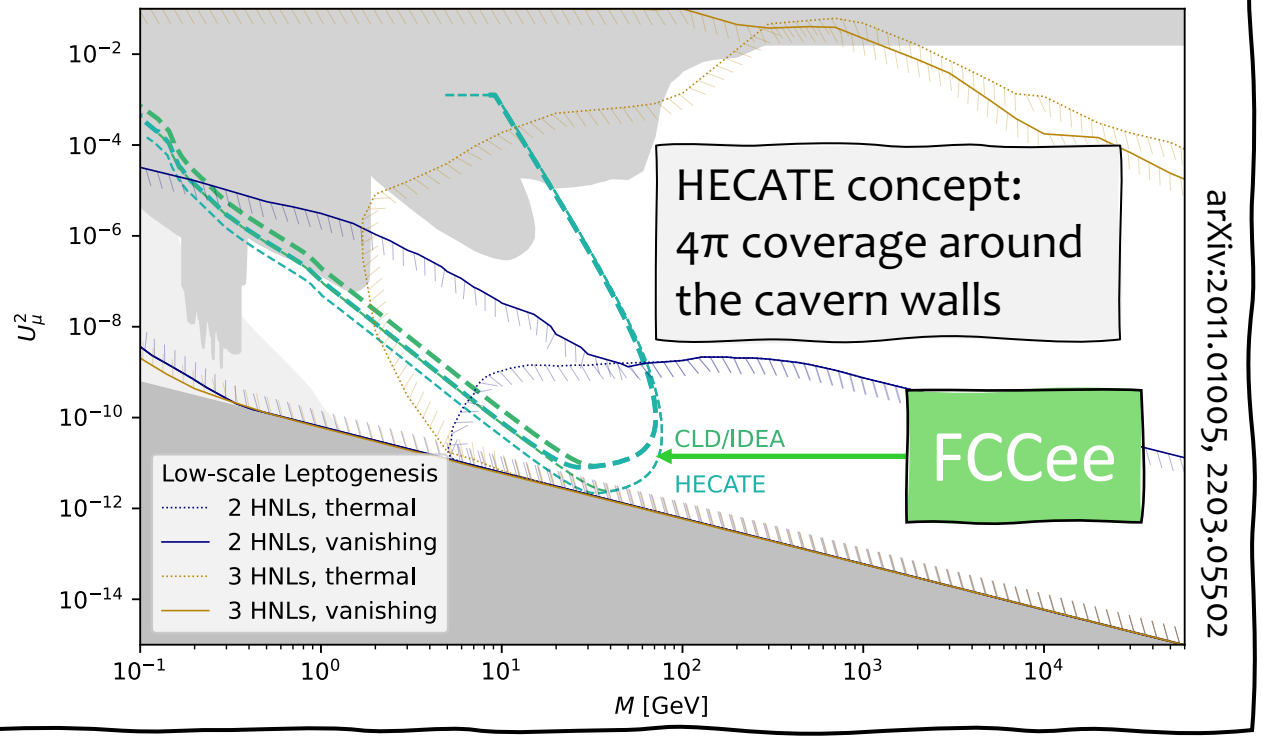
Complementarity of collider and other accelerator experiments

Physics briefing book – Input to EU strategy – arXiv:1910.11775

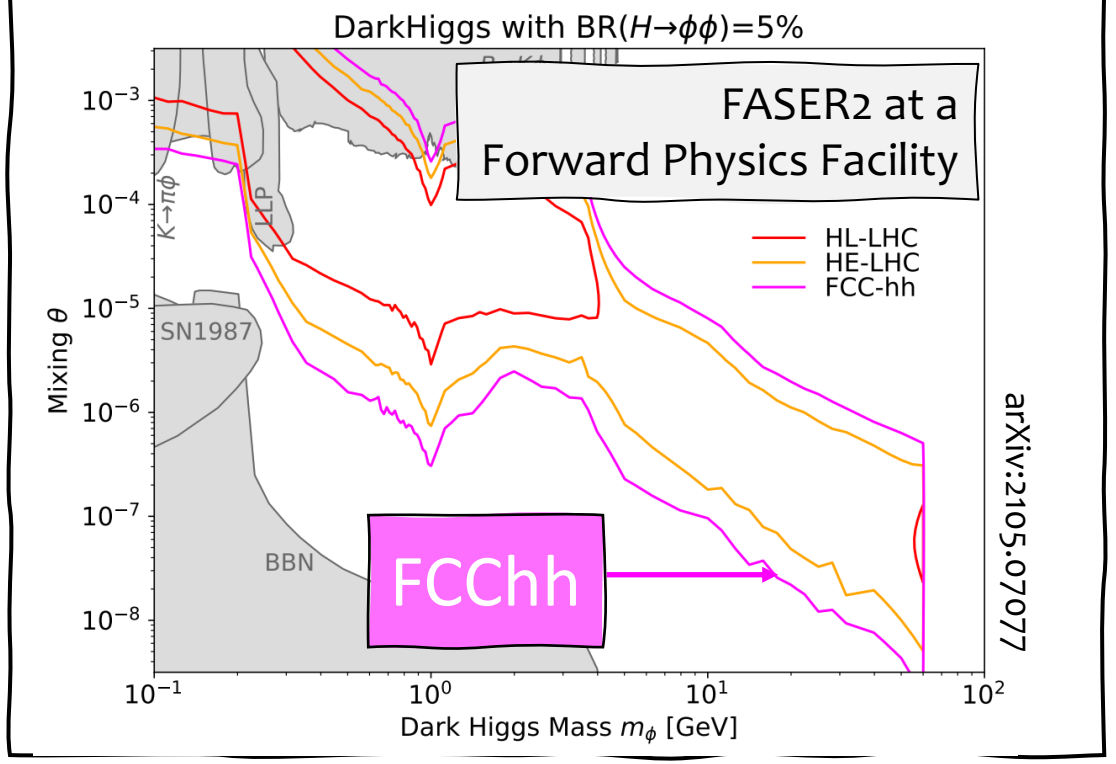
Further opportunities for FIPs at FCC

Two examples. More proposals on arXiv.

At FCCee



At FCChh



Significant opportunities open up, beyond what can be done with conventional collider detectors!
Essential to account for them since the beginning, to minimize overheads later on.