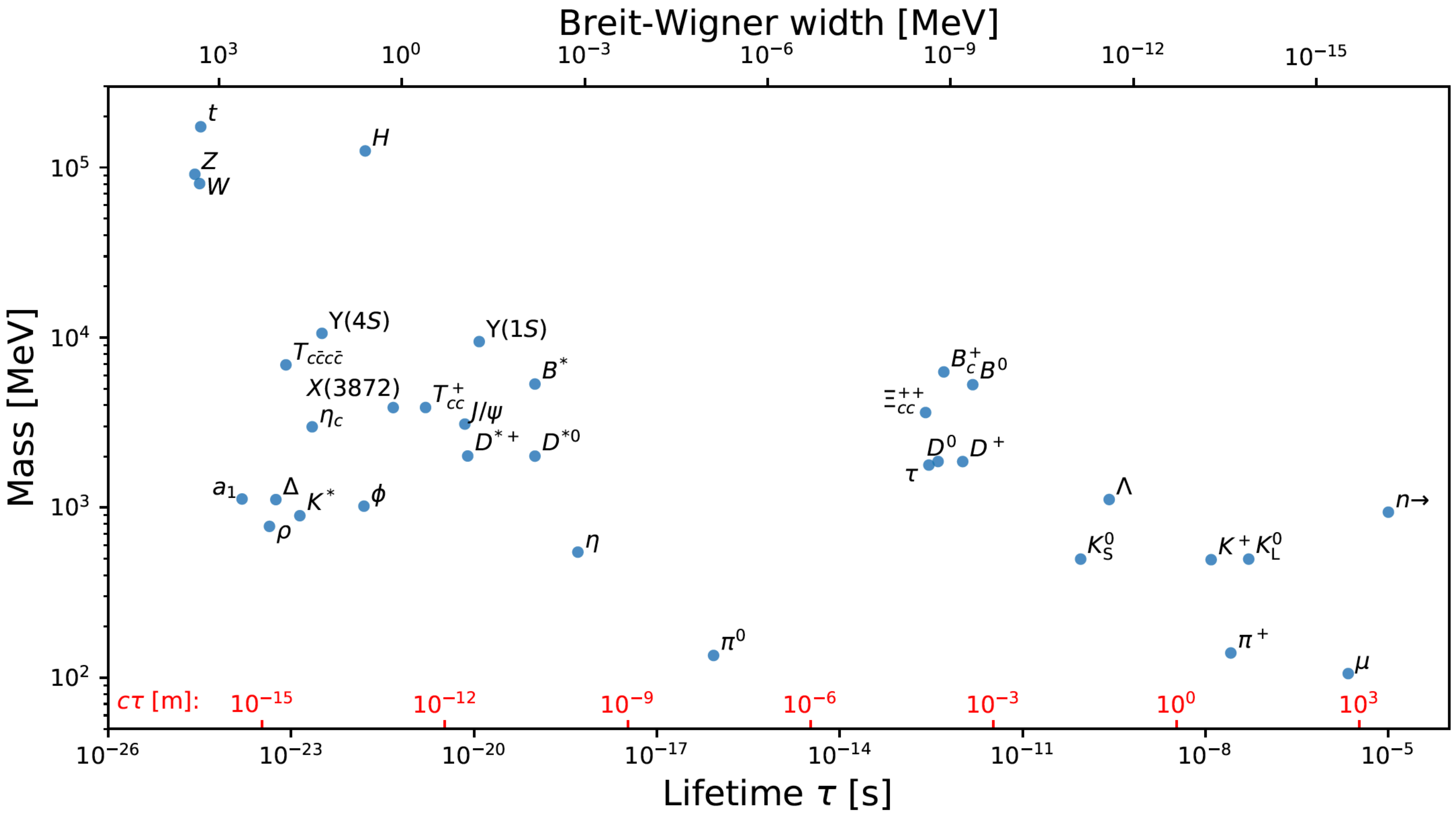
# Non-standard collider signatures

## Long-lived particles

Rebeca Gonzalez Suarez - Uppsala University

# How much a particle lives

## Depends on many factors




Courtesy of Patrick Koppenburg

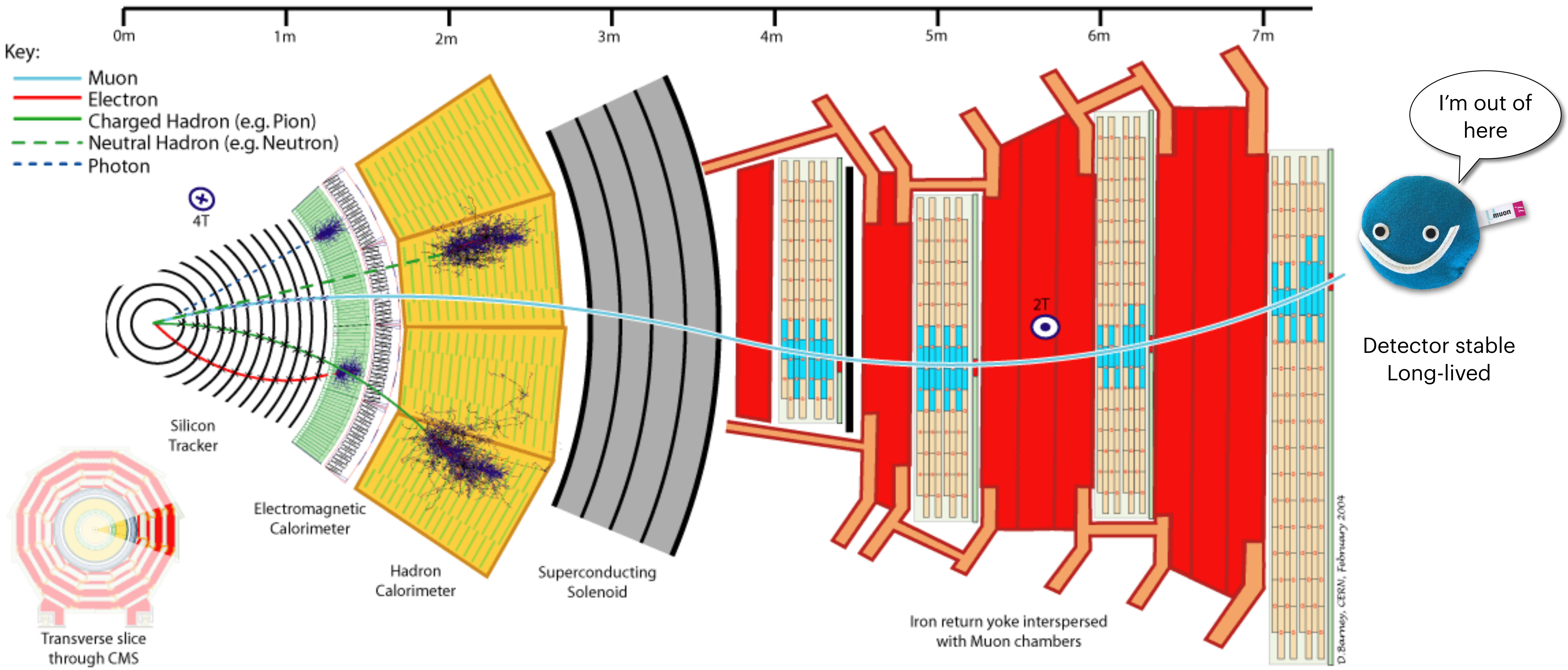
- But the main ones are two:
  - Mass
    - Very massive particles live shortly
  - Couplings
    - Strongly coupled particles live shortly

https://www.particlezoo.net/

# Take for example


Long-Lived
Lives literally forever (stable)
(As far as we know)


?
2.2μs
Feels like it could be short-lived




Detector stable
Long-lived

# But what is a long-lived particle?

- We use **Long-lived particles as an** 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

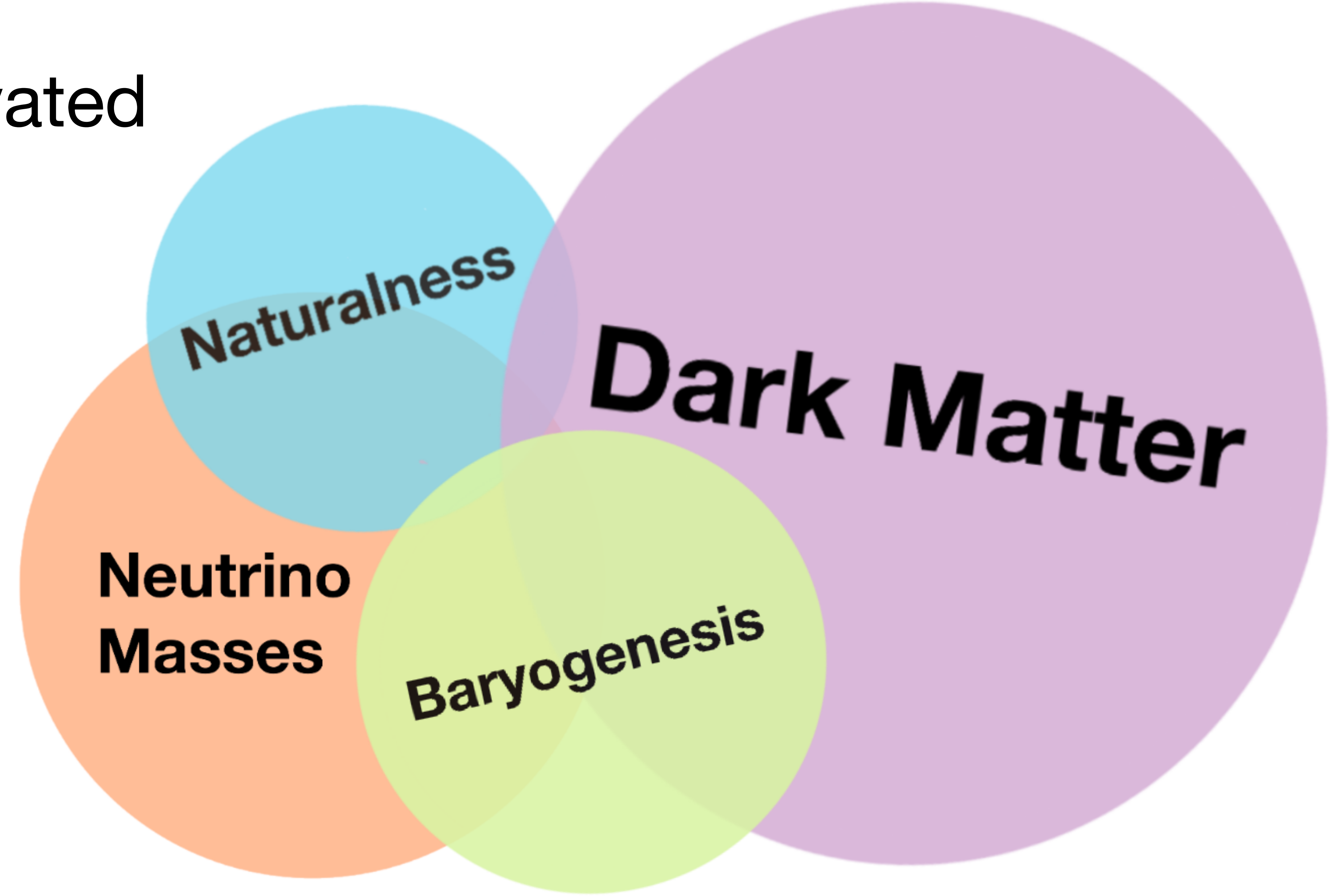

Long-lived
2.2μs


Long-Lived
Stable
(As far as we know)

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

# These New, long-lived particles

- are not a prediction of a single new theory, **they fit into virtually all proposed frameworks for BSM physics**
  - Typically Feebly Interacting
- Theoretically, their presence is strongly motivated



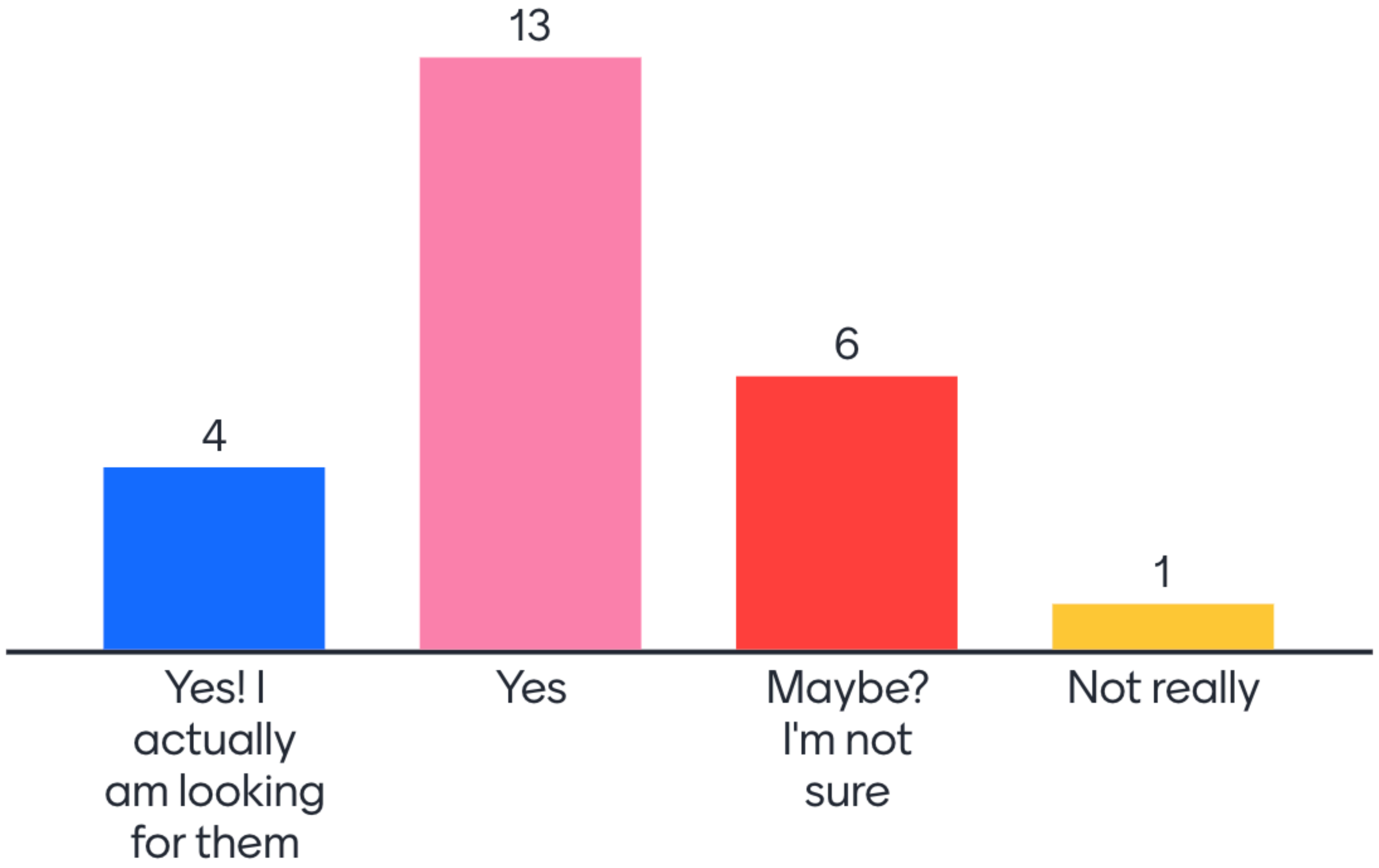

Featured in (including but not limited to):
- SUSY
- Compositeness
- Exotic decays (H, Z, hadrons)
- Hidden sectors

# Quiz stop!

Go to **www.menti.com** and use the code **7980 7878**

# Had you heard about long-lived particles before today?

Mentimeter

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*COST ADVANCED SCHOOL*

# PHYSICS OF DARK MATTER AND HIDDEN SECTORS

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

particleface

LUND UNIVERSITY

*From Theory to Experiment*

Lund, October 18-21st 2021

Invited lecturers

**Sergey Burdin** - Dark Matter direct searches
**Carlos Herdeiro** - Black holes, bosonic stars and ultralight Dark Matter
**Antonio Morais** - Models for ultra-light Dark Sectors
**Alexander Belyaev** - Towards the Consistent Dark Matter exploration
**Kimmo Tuominen** - Dark matter through the Higgs portal
**Andrea Addazi** - Phase Transitions and Primordial Black Holes from Dark Sectors
**Monica D'Onofrio** - The Dark Matter quest at colliders
**Zhi-Wei Wang** - Strongly-Coupled Hidden Sectors
**Giacomo Cacciapaglia** -composite Goldstone Dark Matter
**Antonino Marciano** - Gravitational Wave probes for Dark Matter
**Caterina Doglioni** - Dark Matter complementarity
**Andy Buckley** - Using precision measurements to constrain new physics models with CONTUR
**Rebeca Gonzalez Suarez** - Non-standard collider signatures: long-lived particles
**Pedro M. Ferreira** - Dark phases of multi-scalar models
**Felipe Freitas** - Machine-Learning methods for Dark Sector searchers
**Rui Santos** - Particle Physics anomalies from Dark Matter
**Wei-Chih Huang** - Dark Sectors for matter asymmetry and neutrino physics

Public lecture
The physics garage: From Strings Theory to Pandemics
**Francesco Sannino**

Organising Committee
**Roman Pasechnik (chair)**
**Monica D'Onofrio**
**Caterina Doglioni**
**Rebeca Gonzalez Suarez**
**Antonio Morais**
**Zhi-Wei Wang**

Register at
https://indico.lucas.lu.se/event/2115/

# Talking about dark matter and hidden sectors

## Perfect physics cases for long-lived particles!

- We know very little about dark matter, just that it does not interact with regular matter other than gravitationally
    - Dark matter → does not interact a lot → small couplings → long-lived
- Hidden Sectors that could exist in parallel to the standard model
    - Hidden → does not interact a lot → small couplings → long-lived
- In short:
    - **if you are looking for dark matter/hidden sectors, you need to consider long-lived signatures!**

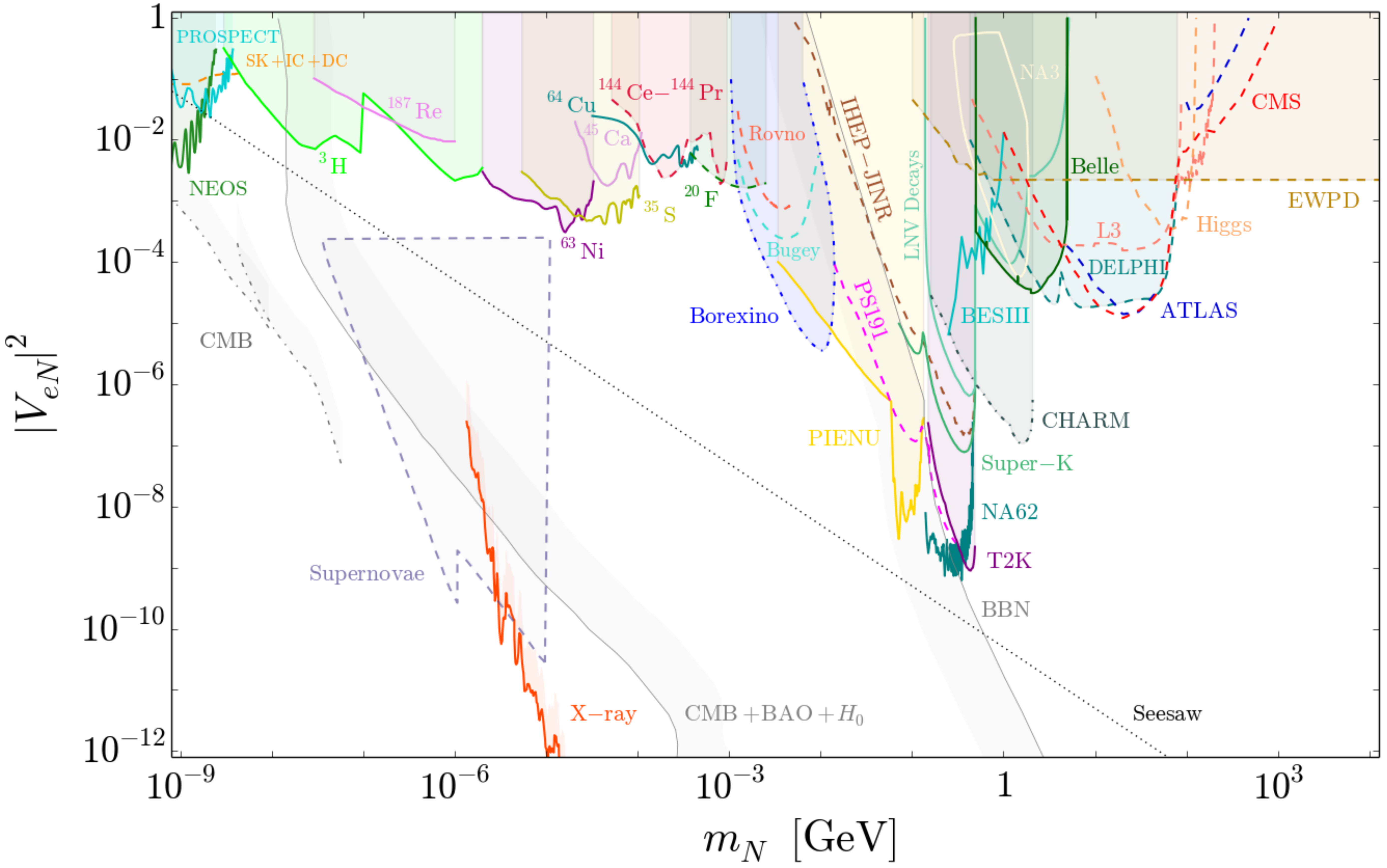
# My favourite long-lived particles

Note: They are all pretty much interconnected

# 1- 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

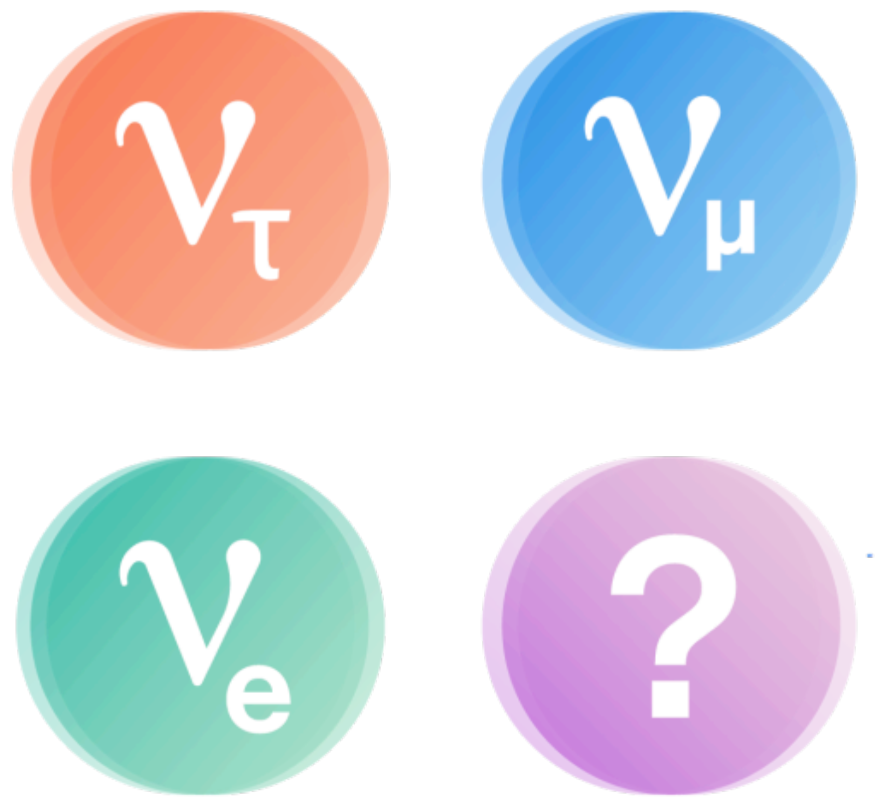



Current constraints on the electron neutrino-sterile neutrino mixing $|V_{eN}|^2$ as a function of the sterile neutrino mass $m_N$ [Ref]

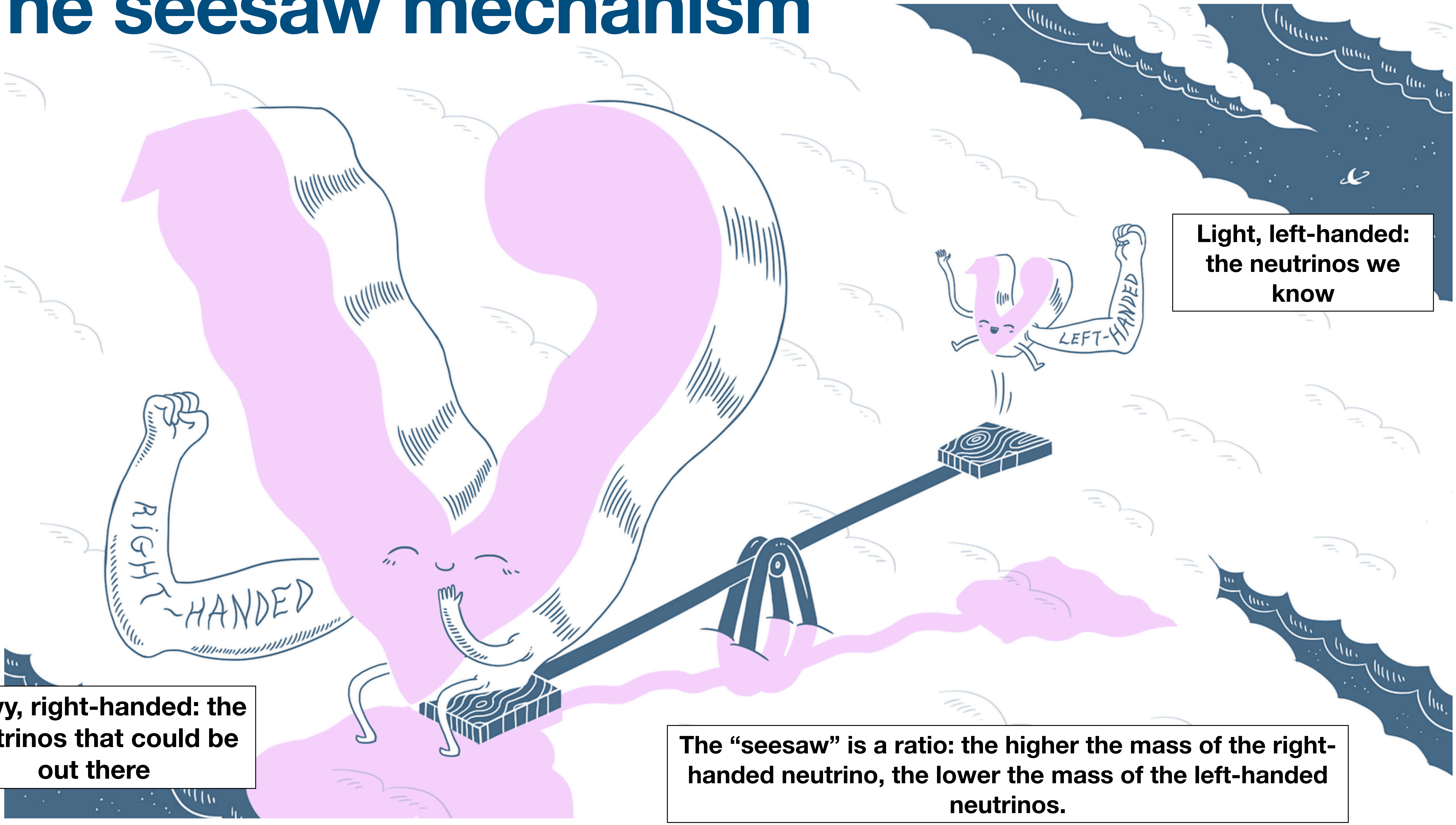
# A BIG question

## Neutrino masses

- Since Neutrino oscillations were discovered, we know that neutrino have non-zero masses
    - But neutrinos are massless in the SM
- The SM needs to incorporate this experimental fact
    - The simplest way to do this is generating Dirac neutrino masses from the Yukawa couplings through the Higgs mechanism, just like for the other fermions.
    - This requires introducing new "right-handed" neutrinos → new HNL



# The seesaw mechanism




Light, left-handed: the neutrinos we know

Heavy, right-handed: the neutrinos that could be out there

The “seesaw” is a ratio: the higher the mass of the right-handed neutrino, the lower the mass of the left-handed neutrinos.

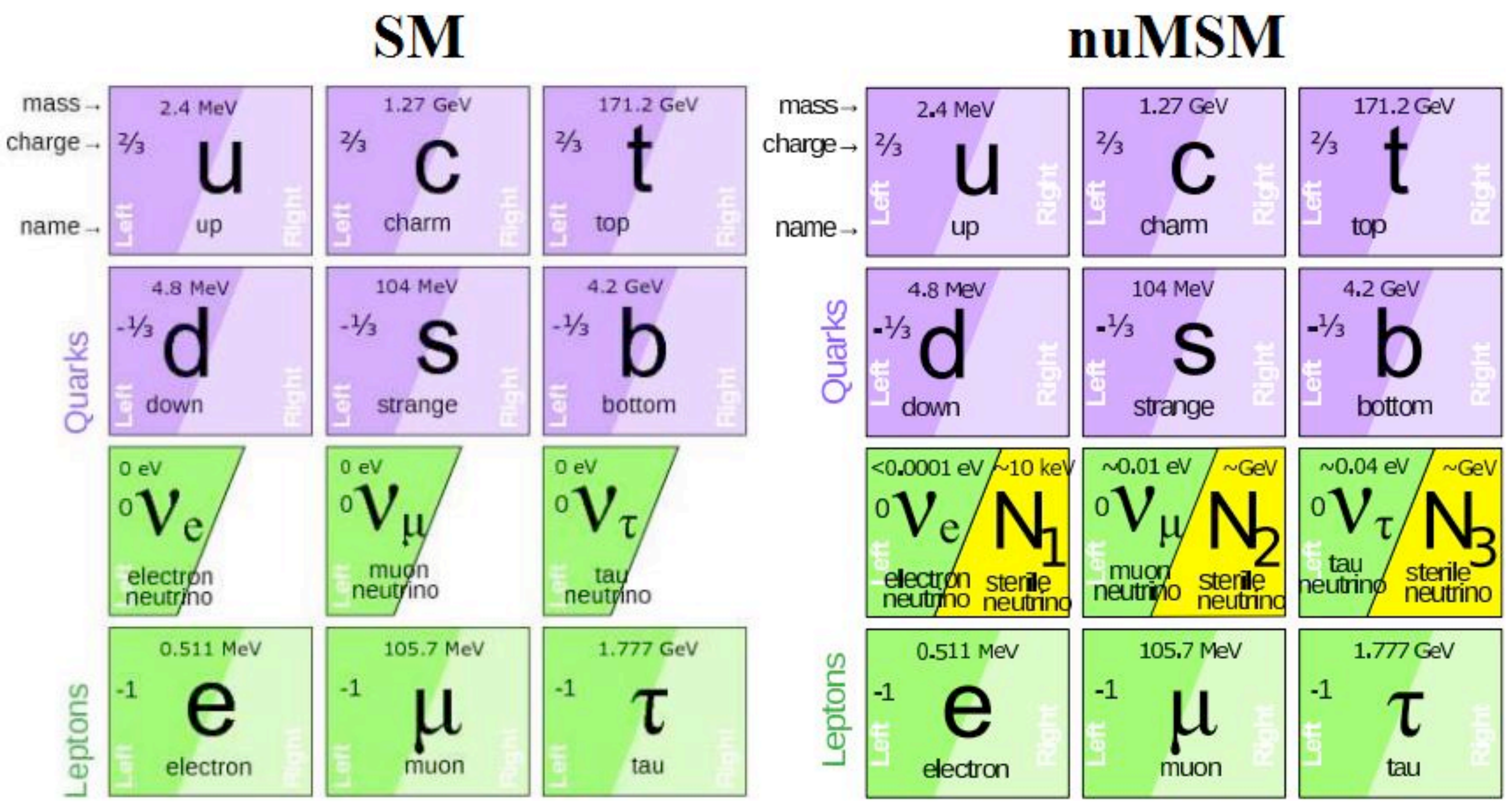
# The matter-antimatter unbalance of the Universe

## Another BIG question

- For the seesaw mechanism to work, if right-handed neutrinos exist, then they would be their own antiparticles.
- If neutrinos are their own antiparticles, it's possible that the antineutrinos emitted during double beta decay could annihilate one another and disappear, violating lepton number conservation via neutrinoless double beta decay.
  - This process would favor matter over antimatter, creating an imbalance
    - Thant sounds familiar

# Dark matter too!

## Conveniently, HNLs also offer a dark matter candidate



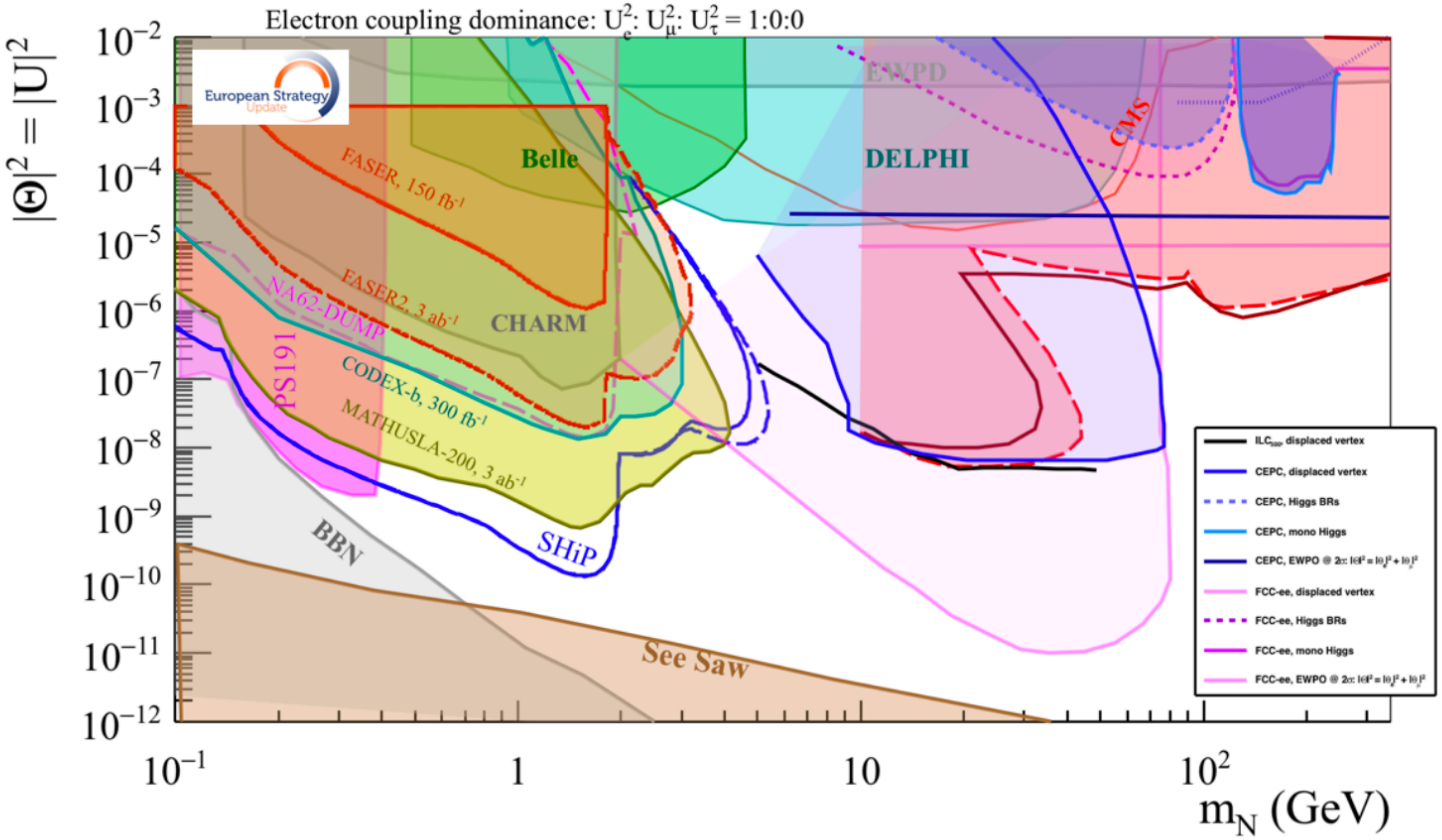

Neutrino Portal

- For example: the “vMSM” is the extension of the Minimal SM (SMS) in the neutrinosector, adding three right-handed neutrinos
  - can explain simultaneously dark matter, the baryon asymmetry of the Universe, and the neutrino masses andmixings observed experimentally
  - The lightest sterile neutrino with mass the keV range → dark matter!

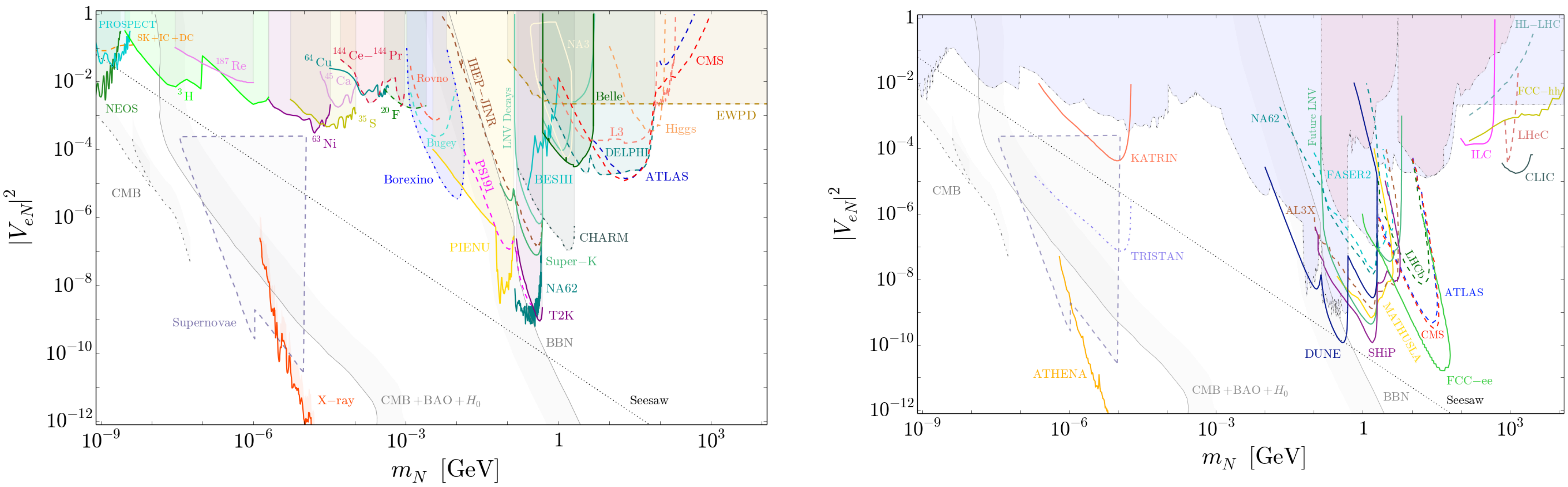
# Complementarity

**Spans several fields: Astrophysics/cosmology, accelerators (collider/beam dump), neutrino**

Could mean a unified Standard Model of particle physics and cosmology



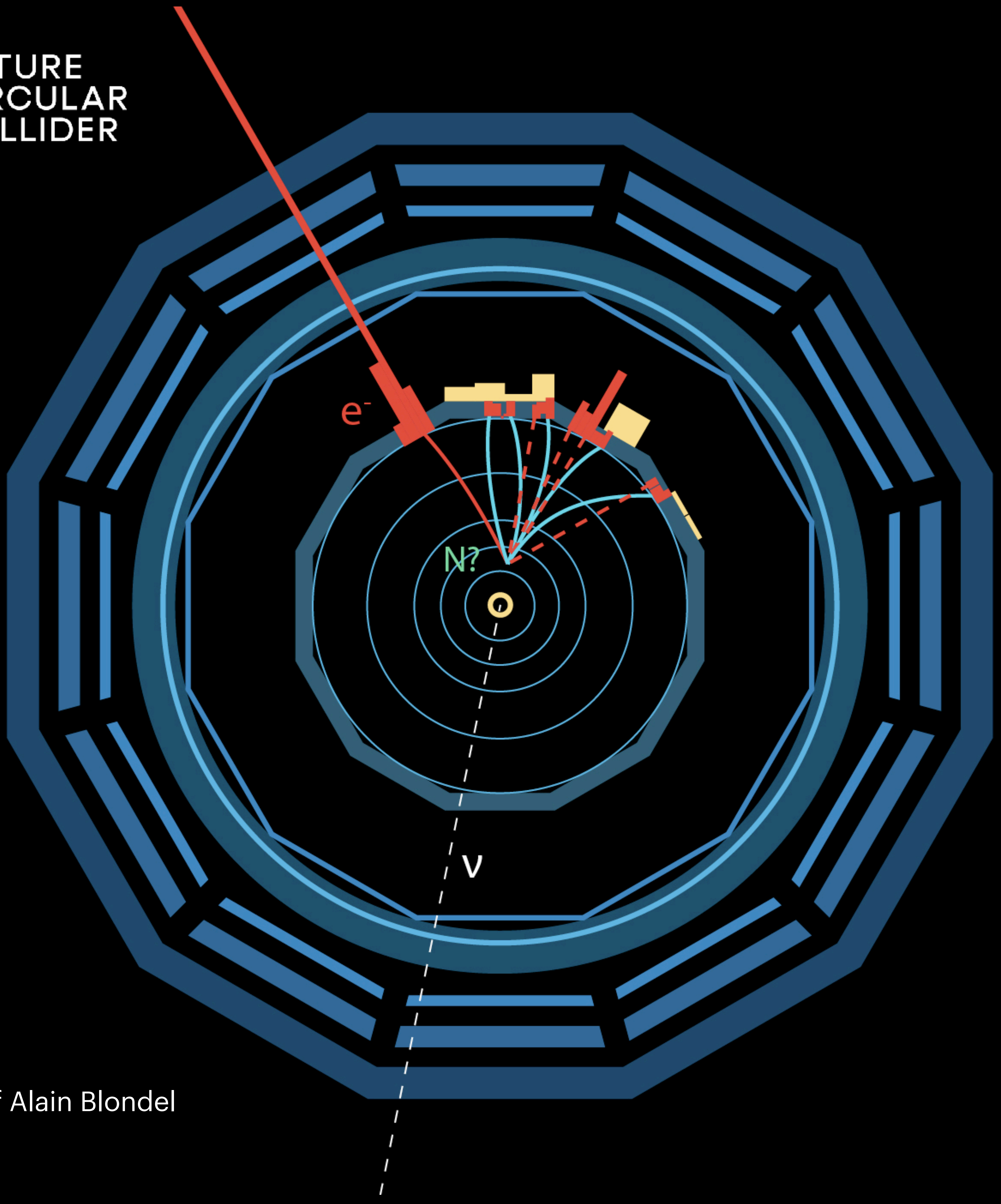

90% CL exclusion limits for a HNL mixed with the electron neutrino, from the Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020 (https://cds.cern.ch/record/2691414/)




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

# Long-lived Heavy Neutral Leptons

FUTURE CIRCULAR COLLIDER




Courtesy of Alain Blondel

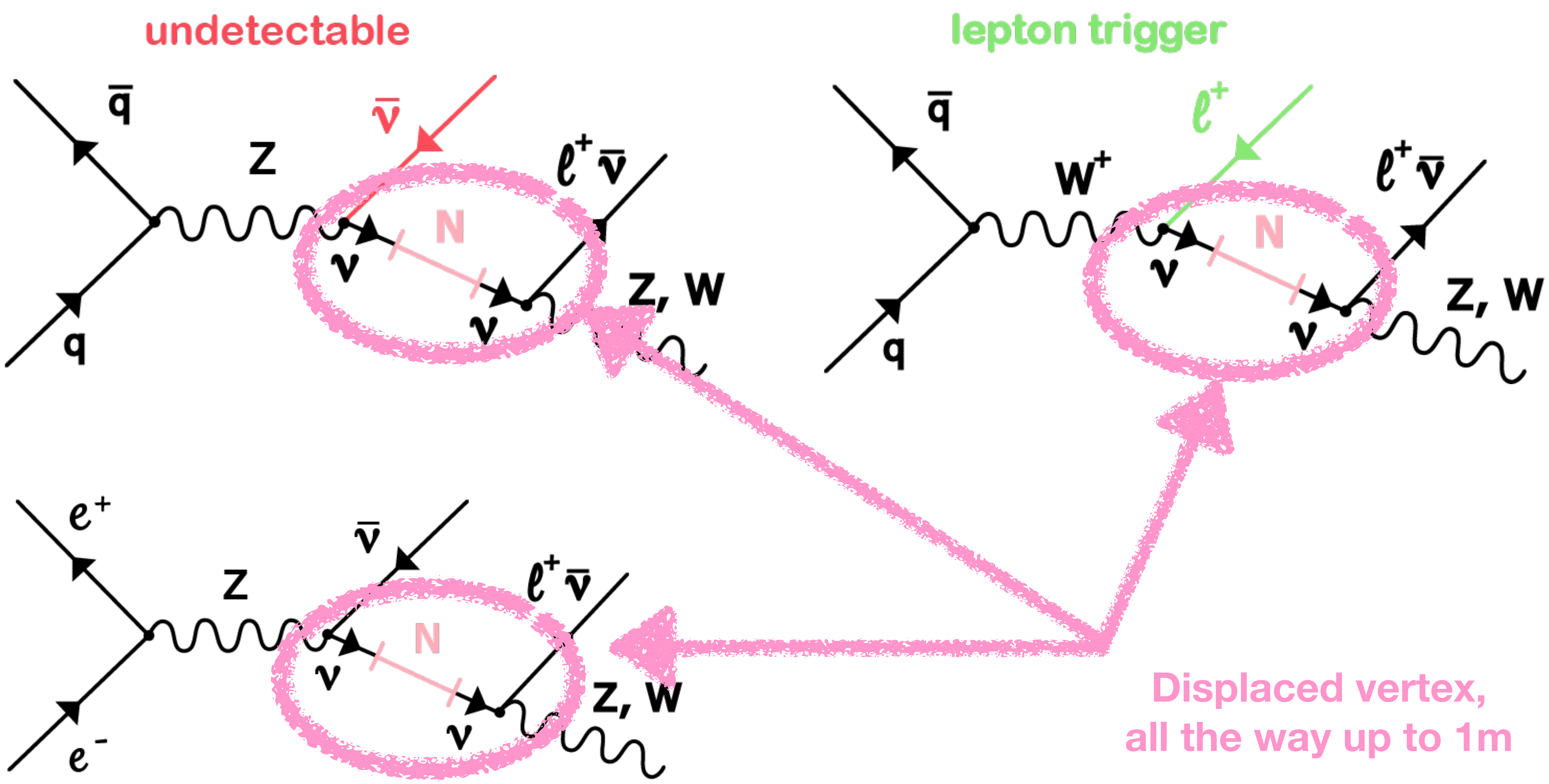
- Many of the current limits cover high neutrino mixing values
- For low values of the neutrino mixing angle, the decay length of the heavy neutrino is significant
  - Long-lived signatures
  - Flagship of the Future FCC-ee
    - Z → νN, N → lW
      - displaced vertex search

# How you generate HNL at colliders?

## Via Z or W decay

**LHC**
(Hadron colliders)
Trigger critical

**Future lepton collider at Z pole**
(FCC-ee)
Much cleaner environment

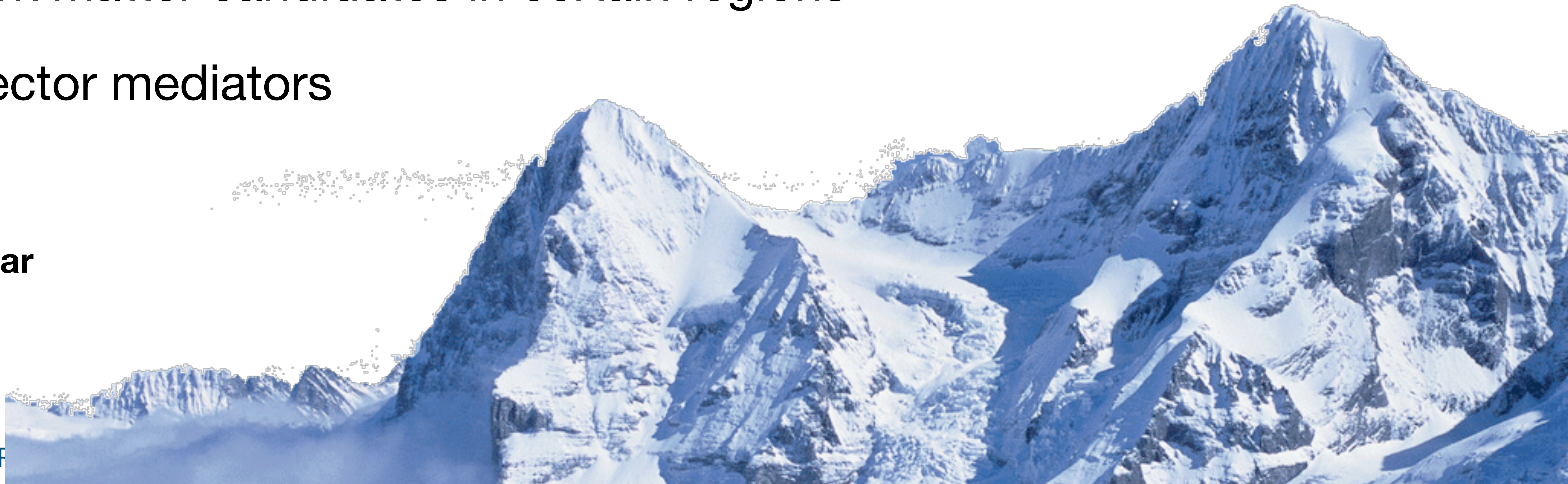


# 2. ALPs

## Another kind of hidden sector

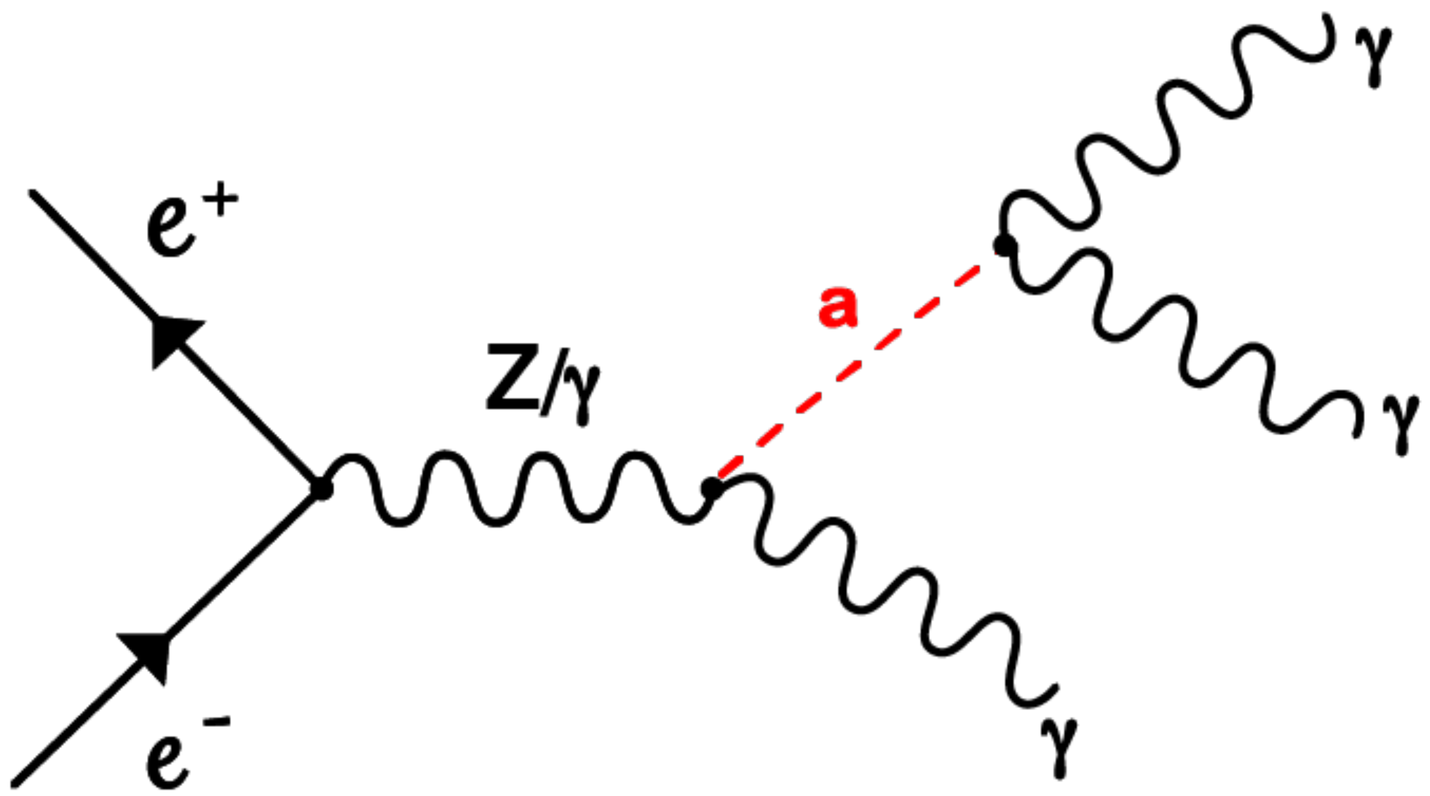
- You will learn EVERYTHING there is to know about dark sectors this week
- ALPs: axion-like particles. Pseudo-scalar particles predicted by BSM models with a spontaneously broken global symmetry (notably string theory), versatile in terms of mass and SM couplings
    - they could be dark matter candidates in certain regions
    - In others: dark sector mediators

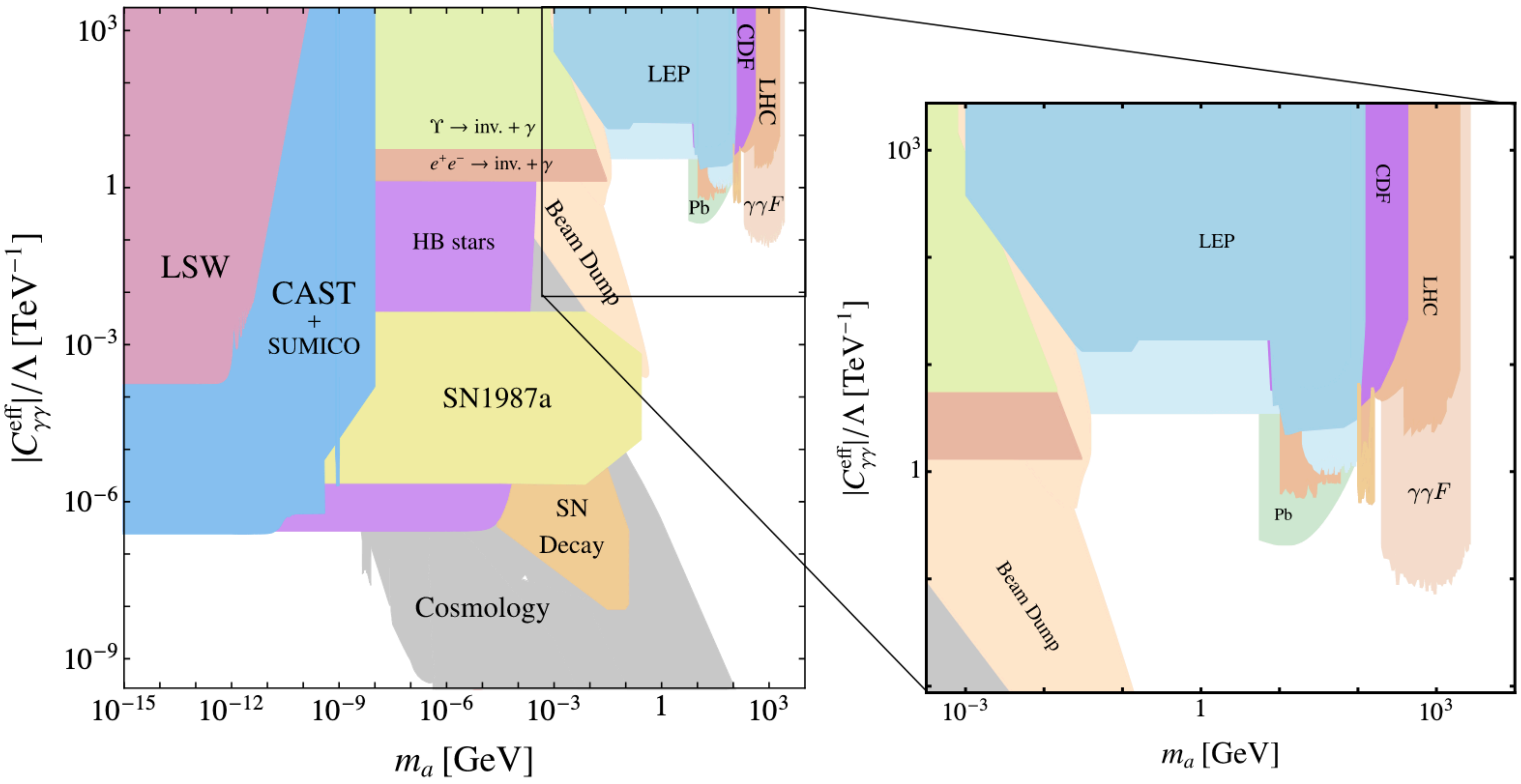
**Pseudo-scalar Portal**



# Long-lived ALPs

- Commonly produced with a photon or a Z decaying into photons
- For small couplings and light ALPs, the ALP decay vertex can be considerably displaced from the production vertex → LLP






Summary plot of constraints on the parameter space spanned by the ALP mass and ALP-photon coupling with enlarged display of the constraints from collider searches from arXiv:1808.10323

# 3. The Higgs boson

## To be more precise, its decays

- We are still getting to know the Higgs boson, the LHC is the only place to study it (for now)
- So far it 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 are widely motivated in (for example)
    - **Twin Higgs** models, **Hidden Valley** models (arXiv:1812.05588), Higgsinos (arXiv:1712.07135), Higgs portal, dark glueball (arXiv:1911.08721) etc etc

**Higgs Portal**

# Quiz stop #2!

Go to **www.menti.com** and use the code **3134 9531**

Mentimeter

# Now it is your turn: which LLPs or BSM models with LLPs are your favorite? you can pick three!

neutrino
dark showers
displaced vertex
muon
heavy neutrino
right neutrinos
fermion dark matter
dark glueball
hoperon
hidden valley
alp
hnls
hnl
axiverse
sterile neutrinos
alps
susy
axion
dark photon
higgs portal
peccei-quinn
dark photons
higgs decays
hidden sector
displaced lepton signatur
susy rpvll
disappearing track
rebeca's dark roomba

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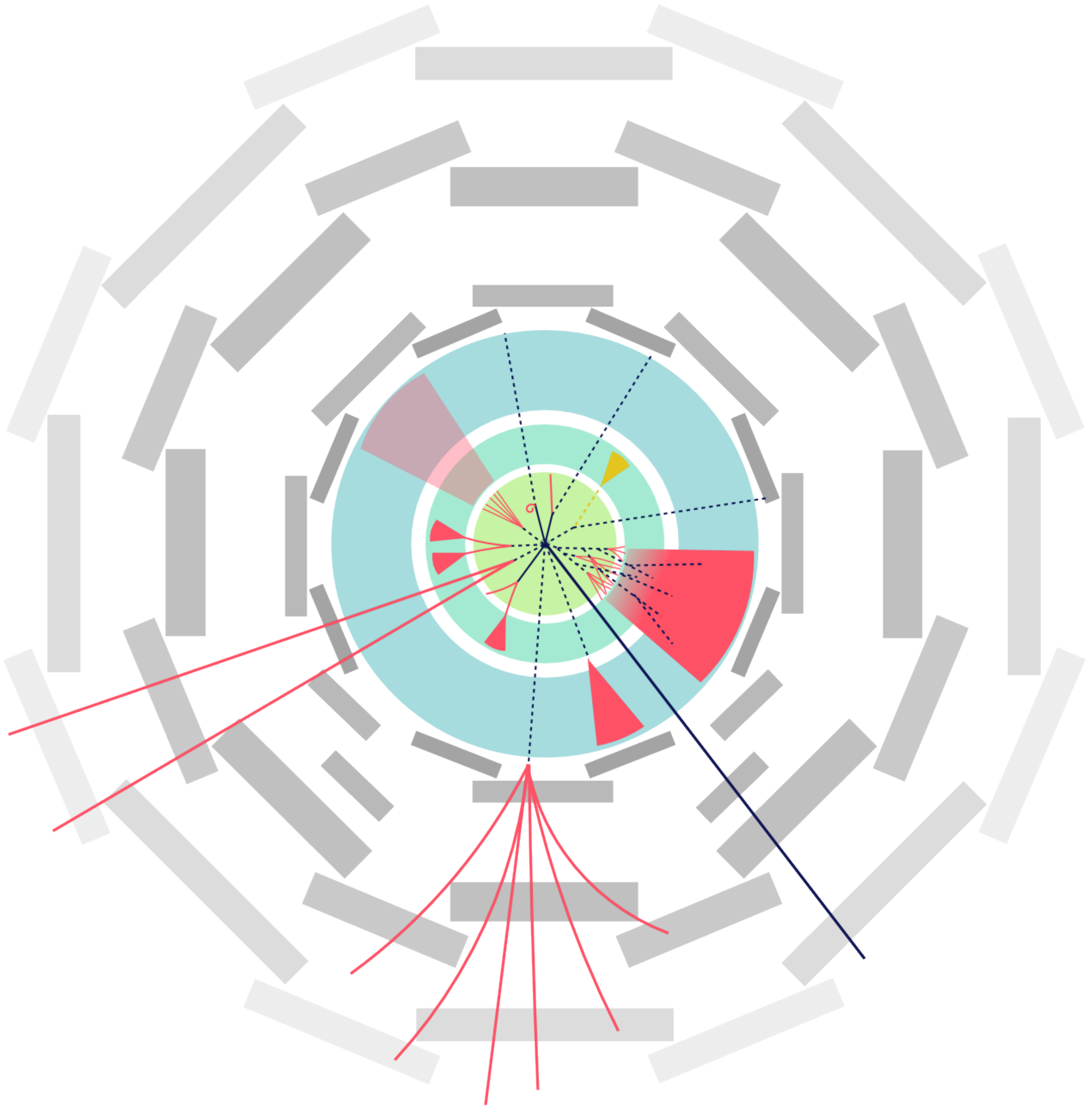
Figure by Heather Russell

# As an experimentalist

## The study of long-lived particles offers something extra!

- A whole catalogue of very exciting signatures!
- And experimentalist don't need to pick a model
- Just to guarantee that LLP signatures are properly identified and reconstructed
- Sadly, that is NOT EASY



# The technical challenges

daunting

# At the LHC

## We push the energy frontier

- As we reach higher and higher energies, we gain access to more massive particles
    - That in turn are shorter and shorter-lived

# Main offenders


The Higgs boson
2012 - LHC
Sort-Lived
$10^{-22}$ seconds
You blink and you miss it!


The top quark
1995 - Tevatron
Sort-Lived
$10^{-25}$ seconds
So short-lived it does not even have time to form hadrons!

# Detecting particles

## At high-energy colliders

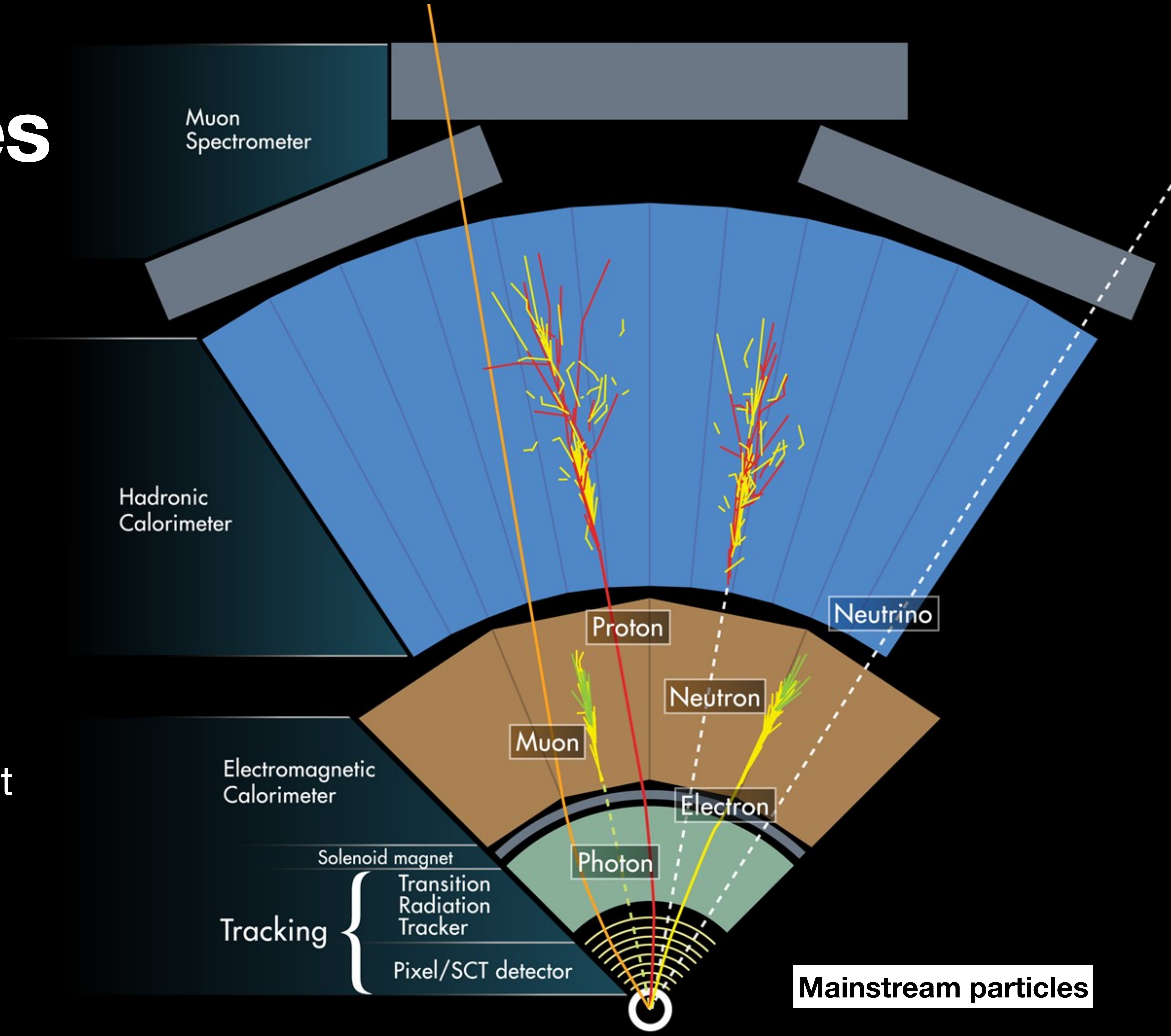
E.g. the Higgs boson at the LHC:

- A Higgs boson is produced and decays $10^{-22}$ seconds after

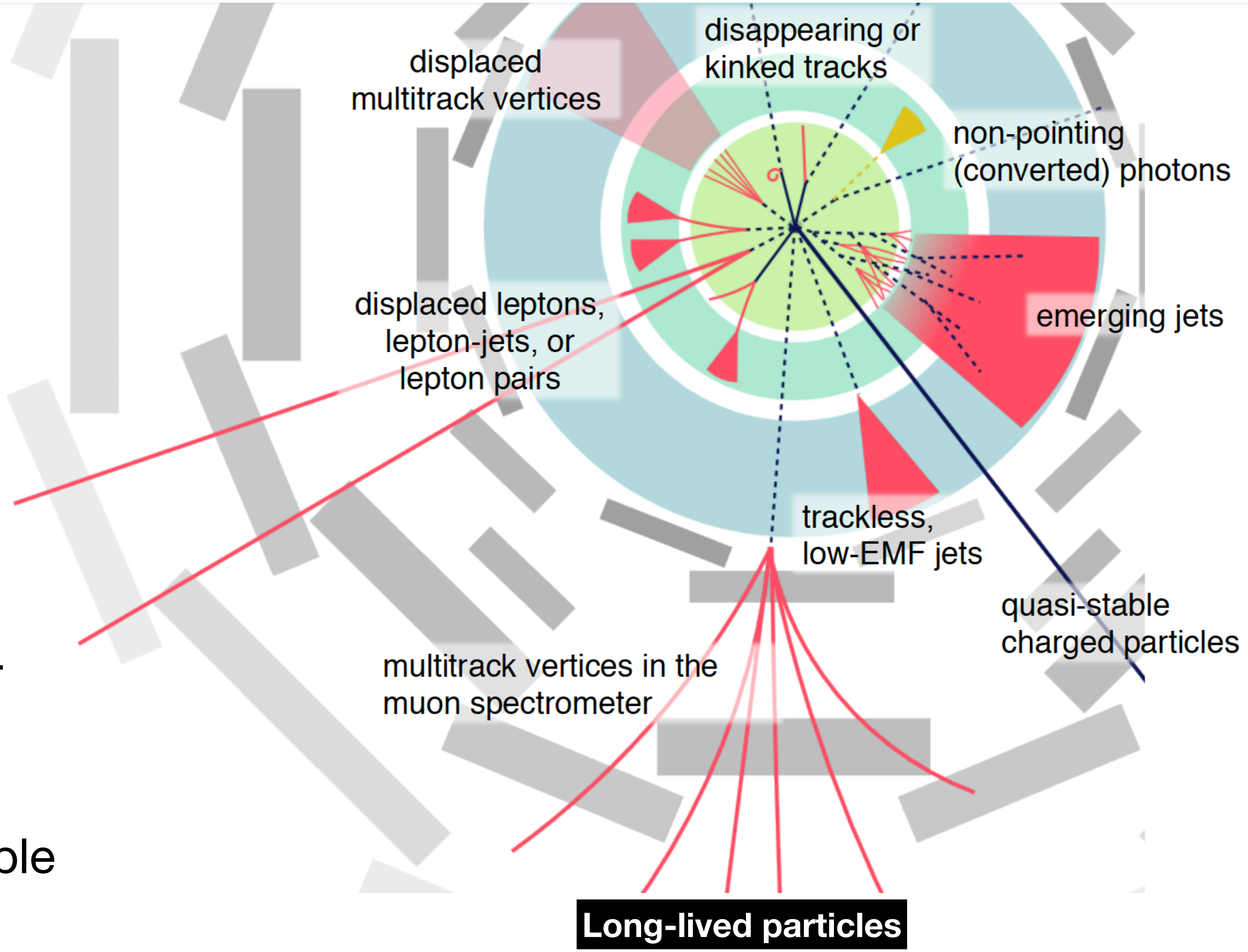
- It often decays into two Z bosons, each of them decaying in about $10^{-25}$ s in e.g. a couple of muons each

- In practice this means that we see 4 muons coming from the collision point

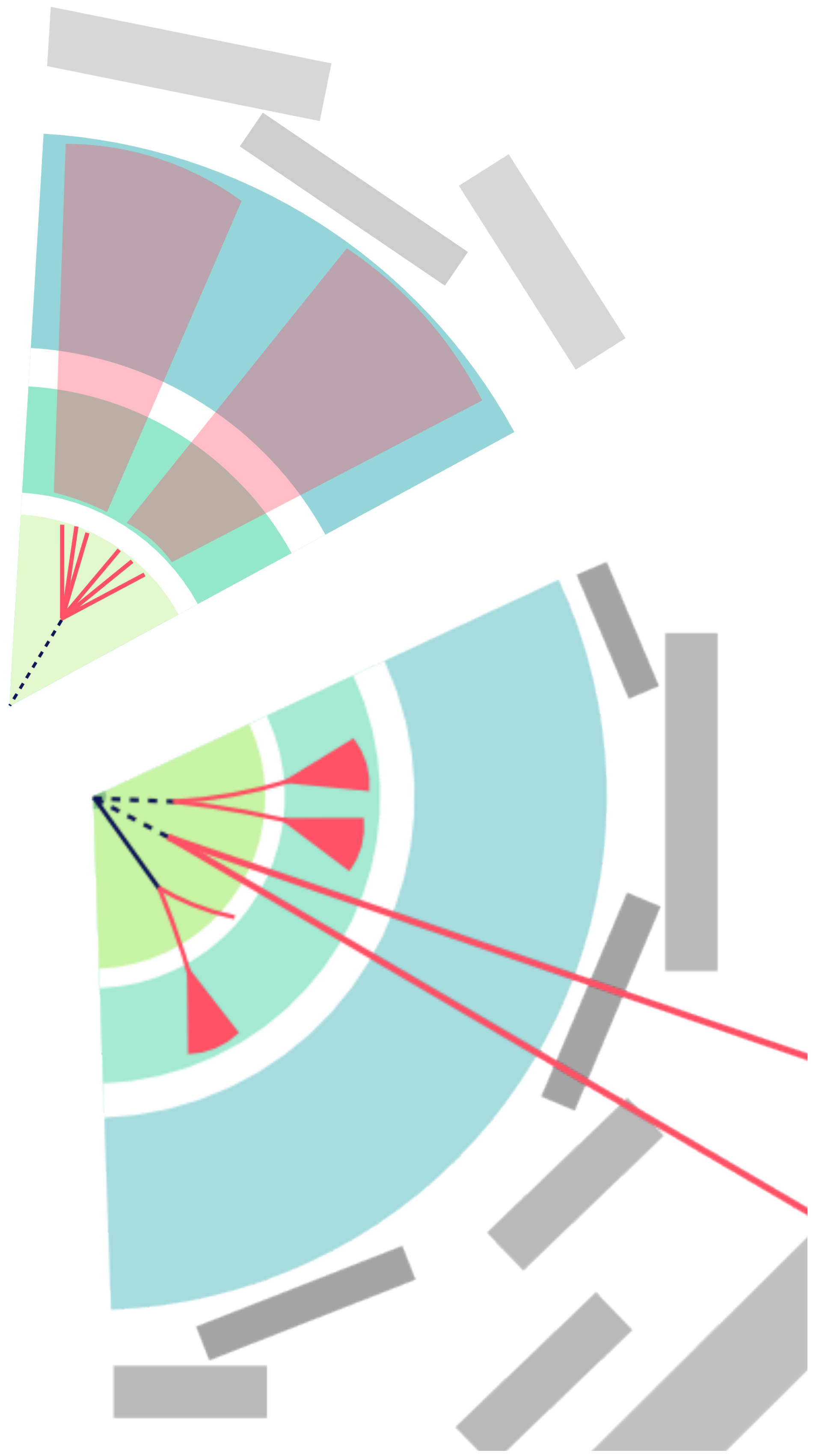
**Our detectors, trigger, and reconstruction are optimized for that!**

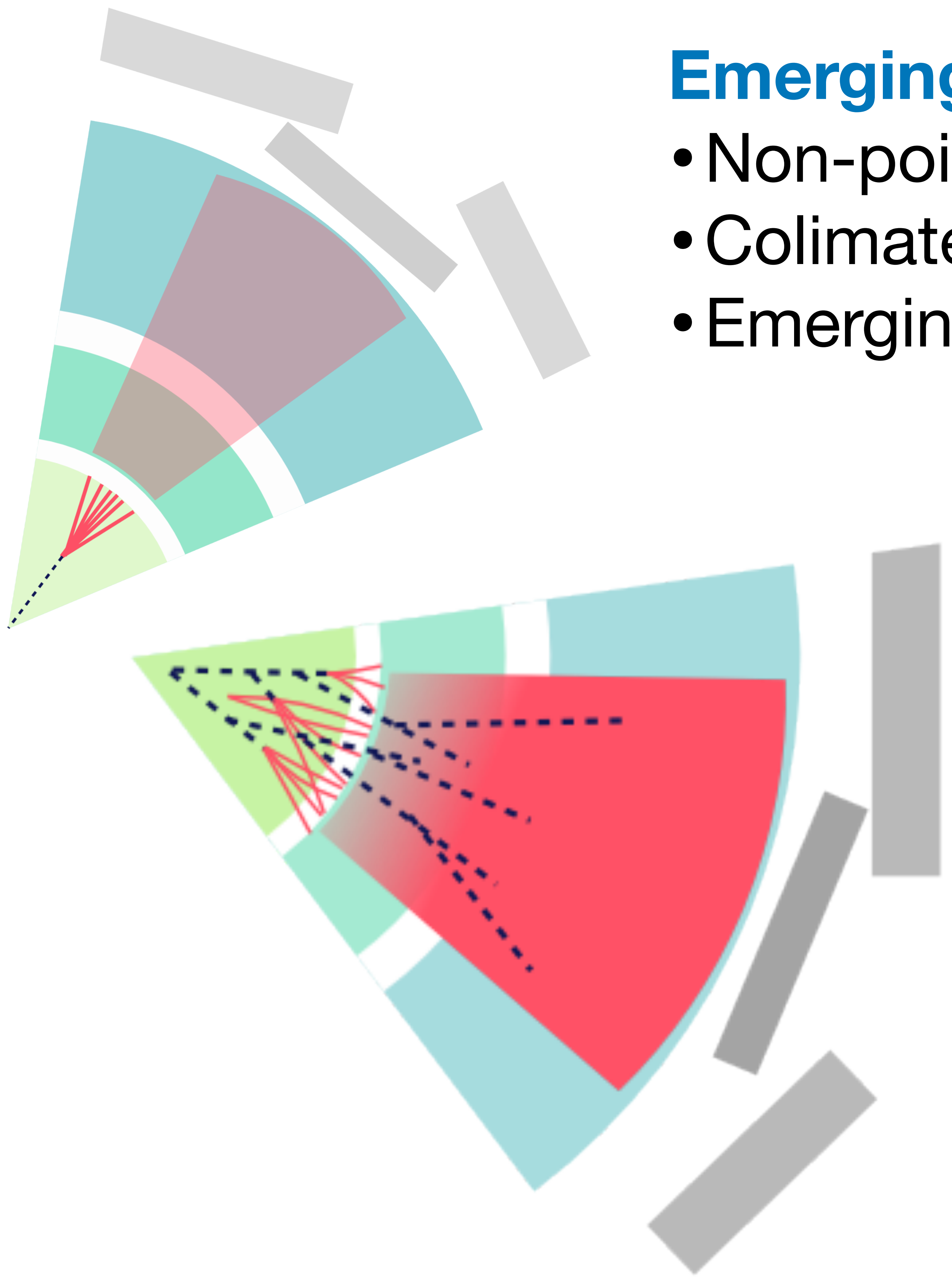


Figures by Heather Russell



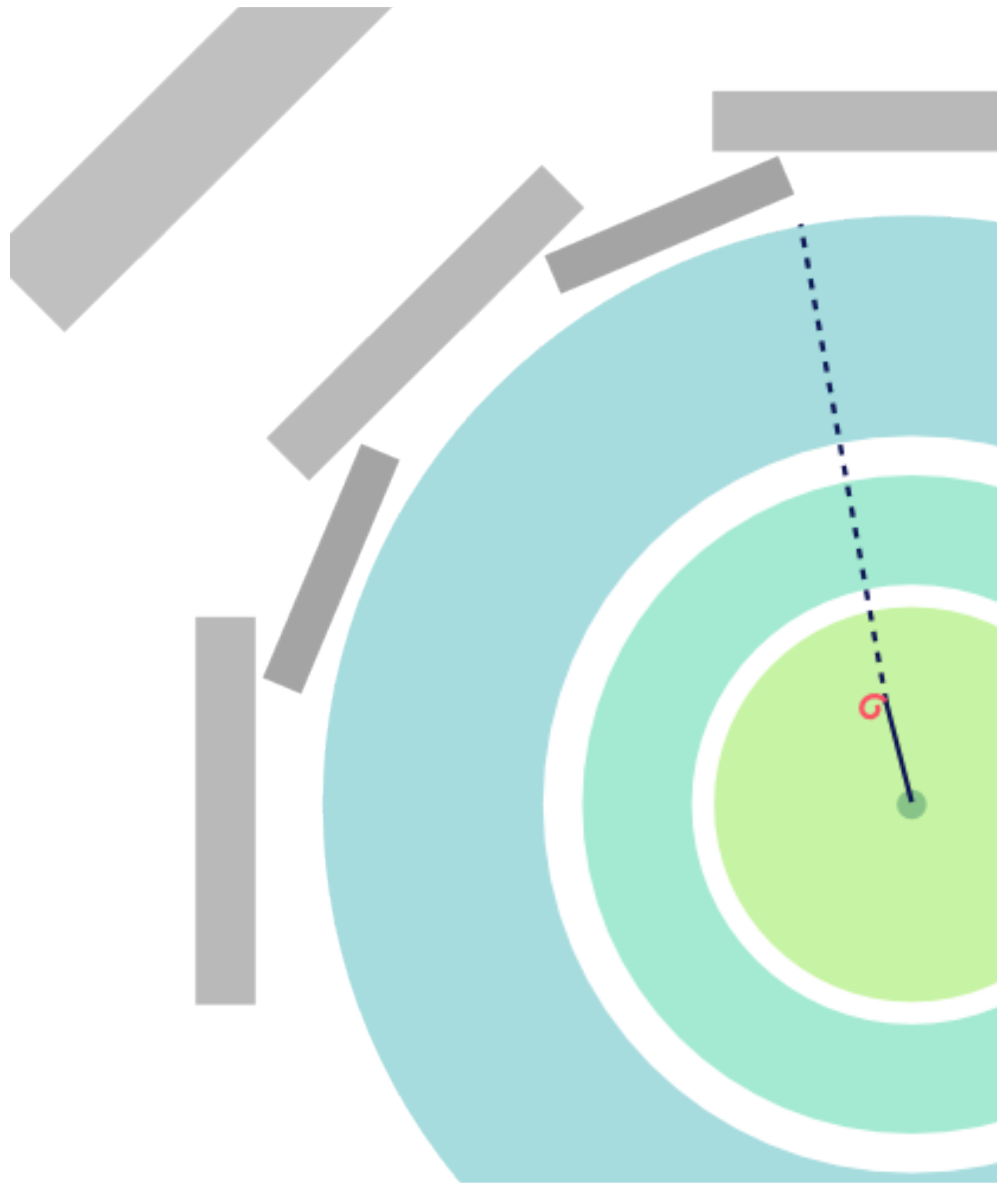

- Long-lived particle searches probe unconventional signatures
  - Displaced, disappearing, emerging, slow, stopped…
- This is a curse and a blessing
  - It makes them clearly different from other processes
    - **Easy to spot! Background free!**
  - It also could make them potentially invisible to current data-acquisition methods
    - **Hard to spot! We may be throwing them away!**





## Emerging/weird

- Non-pointing photons (Calo)
- Colimated objects (Tracker, Calo)
- Emerging jets (Tracker, Calo)

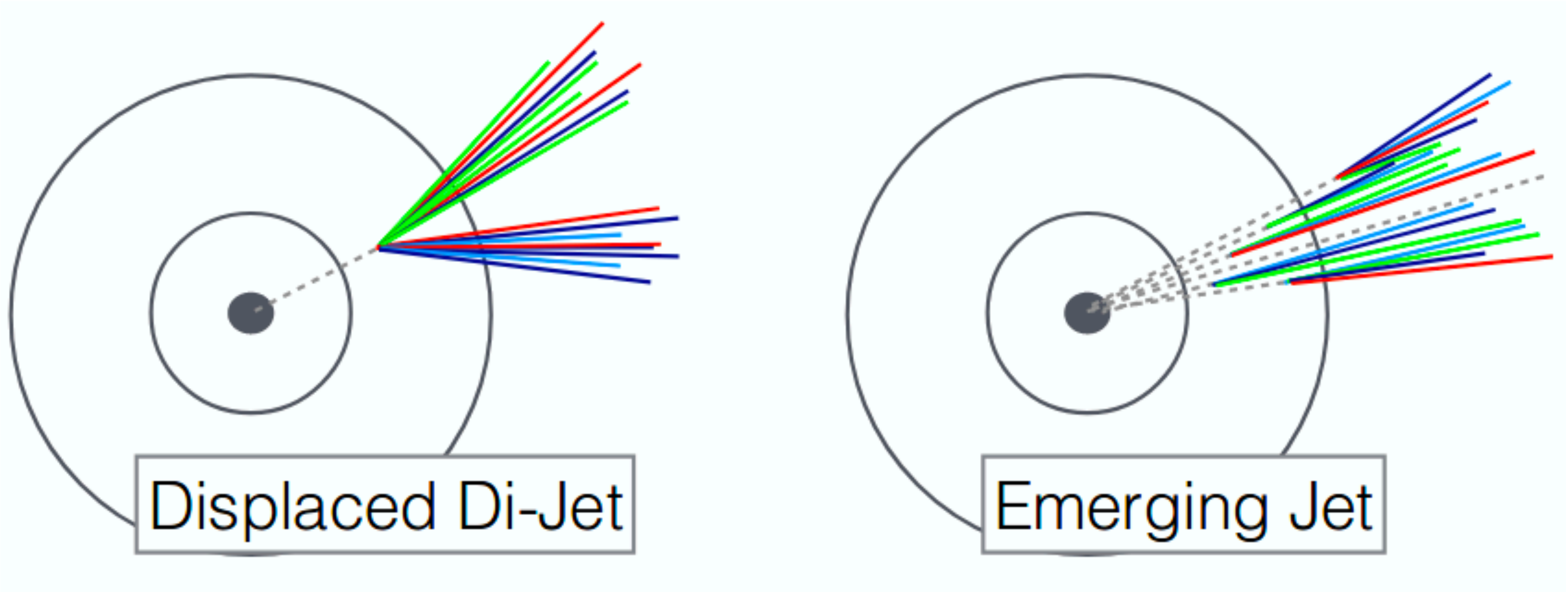


## More Tracking component

- Anomalous dE/dx track
- Fractionally charged, Multicharged particles..
- Short (disappearing, kinked) tracks

## Displaced/Delayed stuff

- Displaced vertices and tracks (Tracker, Calo)
- Delayed/displaced jets (Tracker, Calo)
- Stopped particle decay (Timing!)



# Are we working on this?

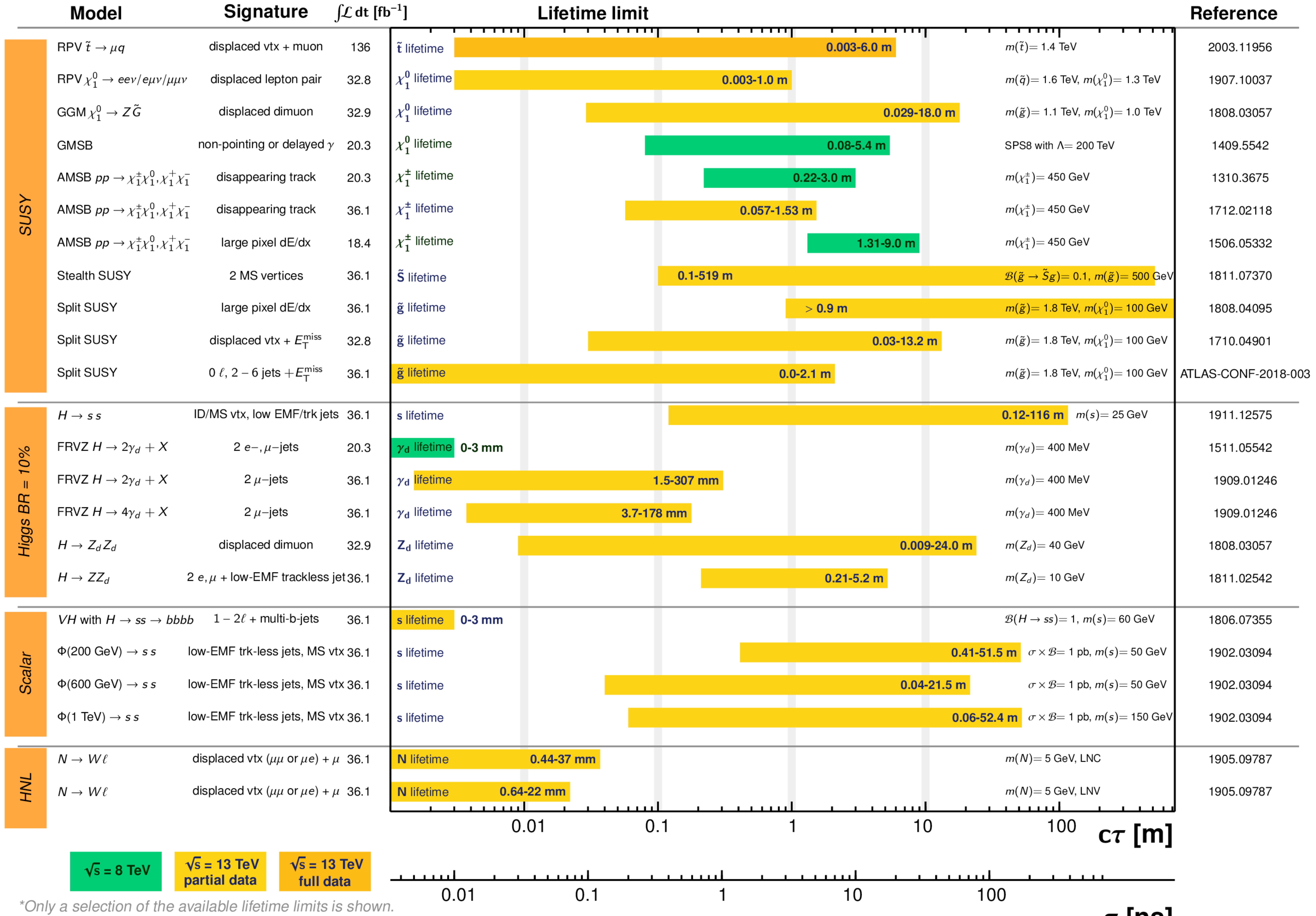
- Yes, since the start of the LHC, at LEP, and the Tevatron…
- Up until 2016 however, LLP searches were considered fringe, today they make up less than 10% of our exotic searches
- But they are starting to pick up a lot of interest
  - LHC Long-lived Particles Working Group (LHC LLP WG)
    - https://lpcc.web.cern.ch/lhc-llp-wg
  - LHC Long-lived particle community workshops
    - https://longlivedparticles.web.cern.ch/

# ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: May 2020

**ATLAS** Preliminary

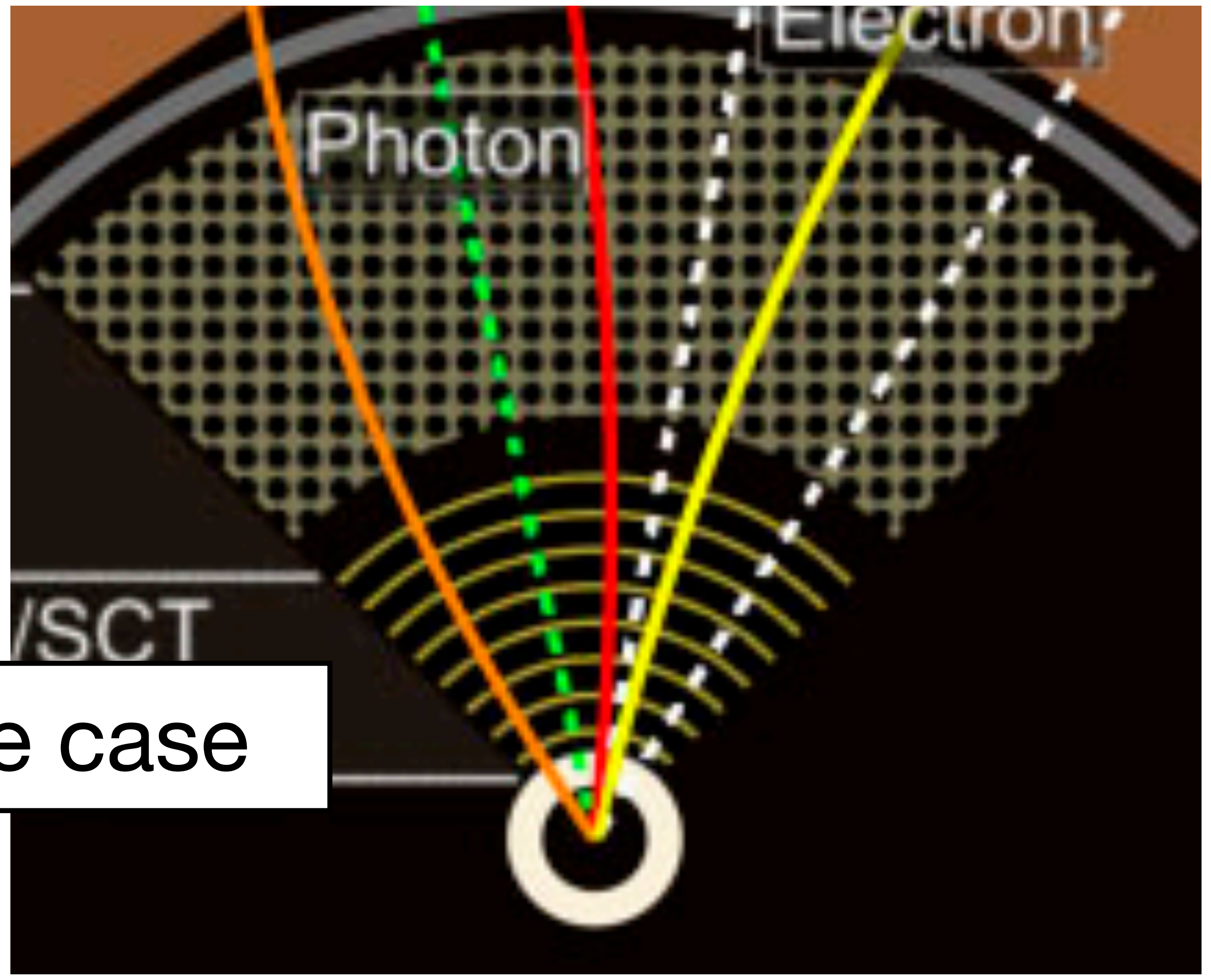
$\int \mathcal{L}\,dt = (18.4 - 136)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV



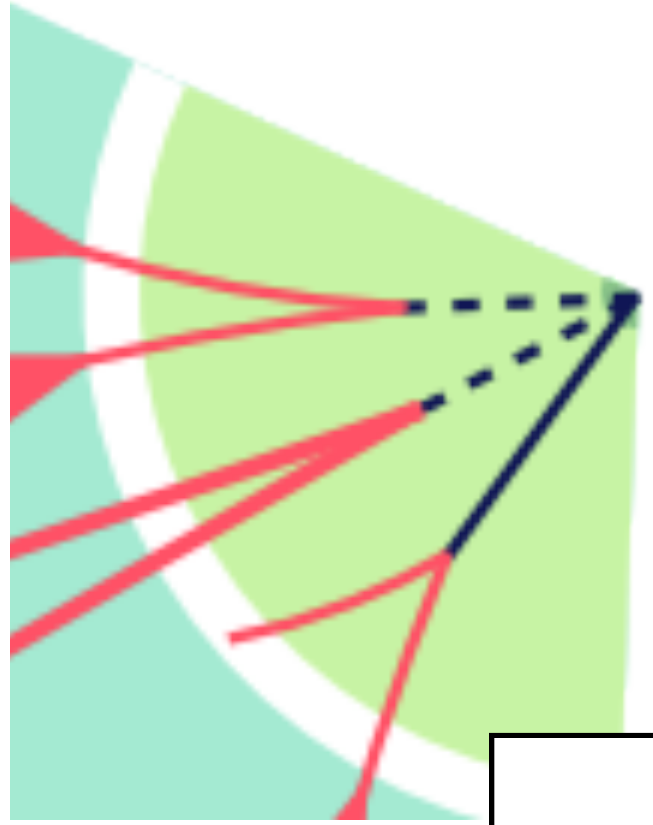

*Only a selection of the available lifetime limits is shown.

# Paradigm shift

- Looking for this kind of signatures STILL represents a paradigm shift from the usual approach to hunting for new physics
- Implies exploiting the detectors in ways they were not designed for




Use case



Displaced vertices/tracks

# Roadblocks

- Need for **specialized reconstruction algorithms**
  - Especially clear in the **Tracker** (less utilized subdetector in LLP so far)
- Very low background searches, but affected by instrumental effects, not well-modelled in the simulation
- Last, but not least: **THE TRIGGER!**

# Trigger matters

- We have 1.7 billion collisions per second and ATLAS and CMS cannot record and process all of them
  - Complicated Trigger and Data Acquisition systems decide what to keep

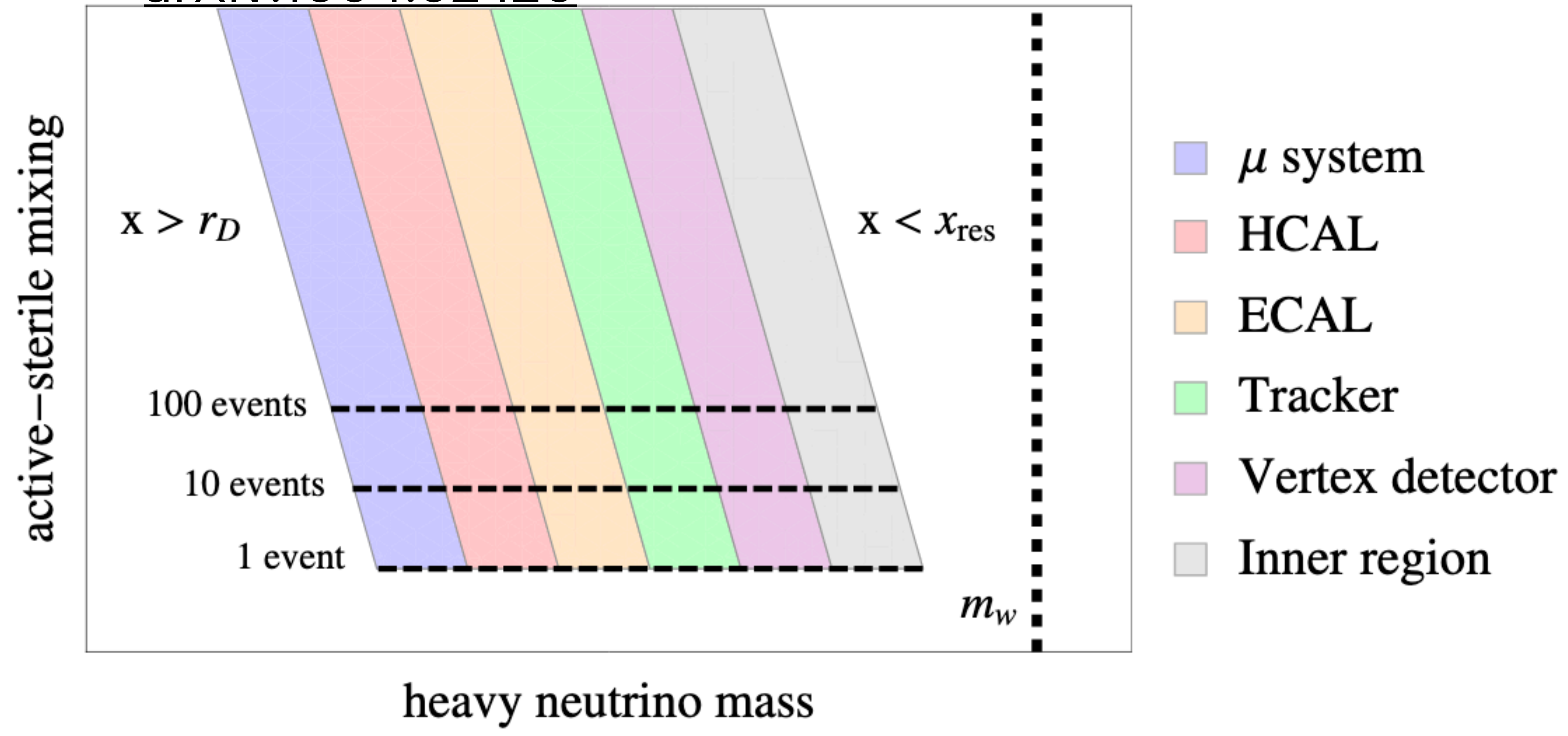
- ATLAS does this in two stages
  - Level-1 hardware trigger (calorimeter and muon detectors). The decision to keep an event is made less than 2.5μs
    - It saves up to 100,000 events/s for the next step
  - High-Level Trigger (HLT), software based
    - Does some reconstruction, selects ~1000 events/s for offline analysis.

# Filtering out things you do not want

- In the case of LLP, if you do not filter them "in" then you may be actively filtering them "out"
- Most public LLP analyses use custom trigger paths
  - + Relying on objects produced together with the LLP (MET, leptons, jets)
  - - Most trigger reconstruction algorithms assume prompt particles
  - - There is no track information at decision level, so we could be missing many interesting events
- Are we missing LLPs decaying in the tracker?
  - Probably yes

# This won’t be different at future colliders

arXiv:1604.02420




Sensitivity of different detector components to HNL as a function of the mixing parameter and mass

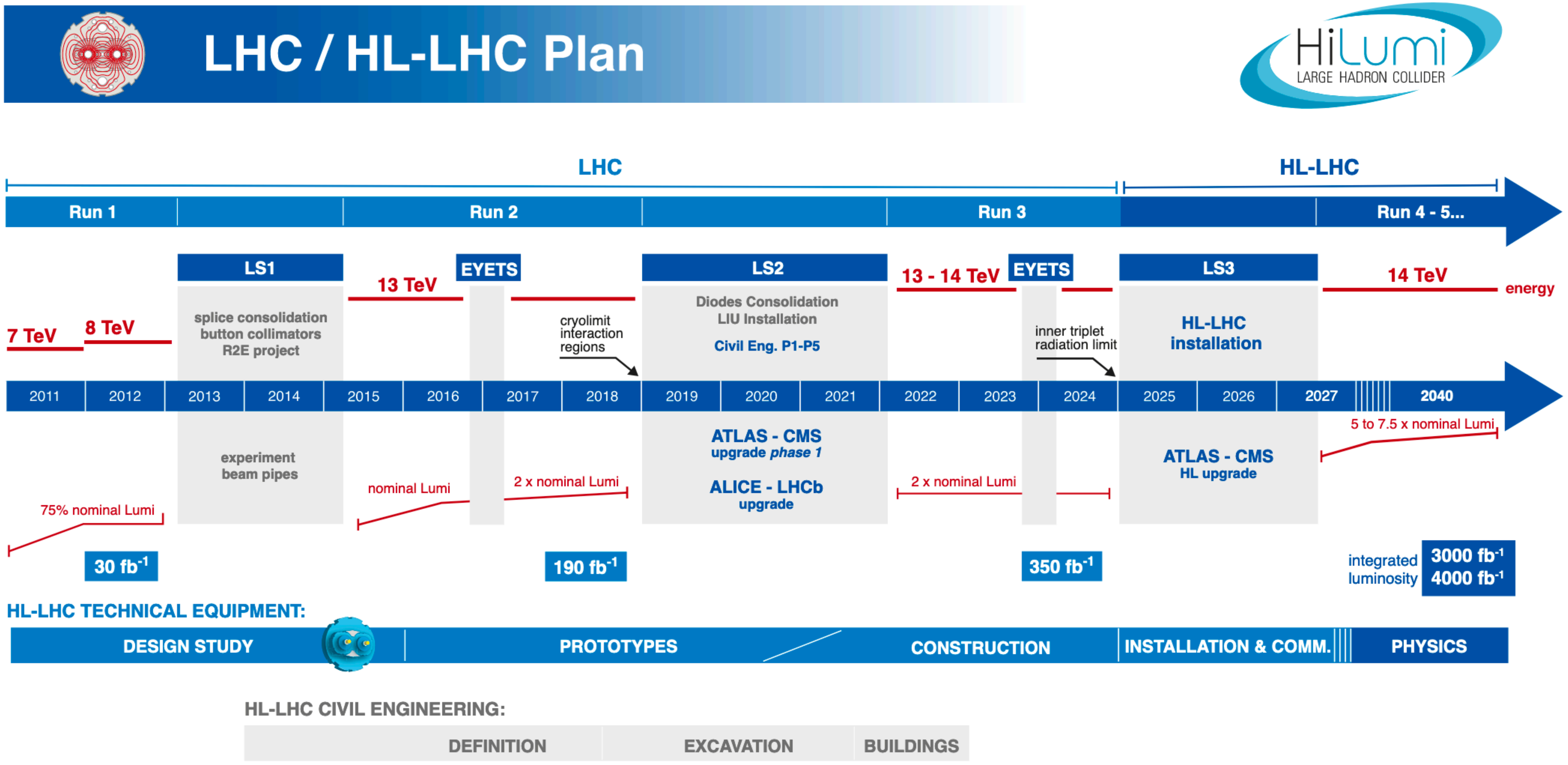
- At this point we have two ways to go:
  - Design the future detectors as usual and then try to make the best out of them for LLPs
    - which can be done but won’t be easy as we know from the experience at the LHC -and before-
  - Design the future detectors with LLP in mind, prioritising for example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

# The next collider

Is closer than one would think

# The High-luminosity upgrade of the LHC

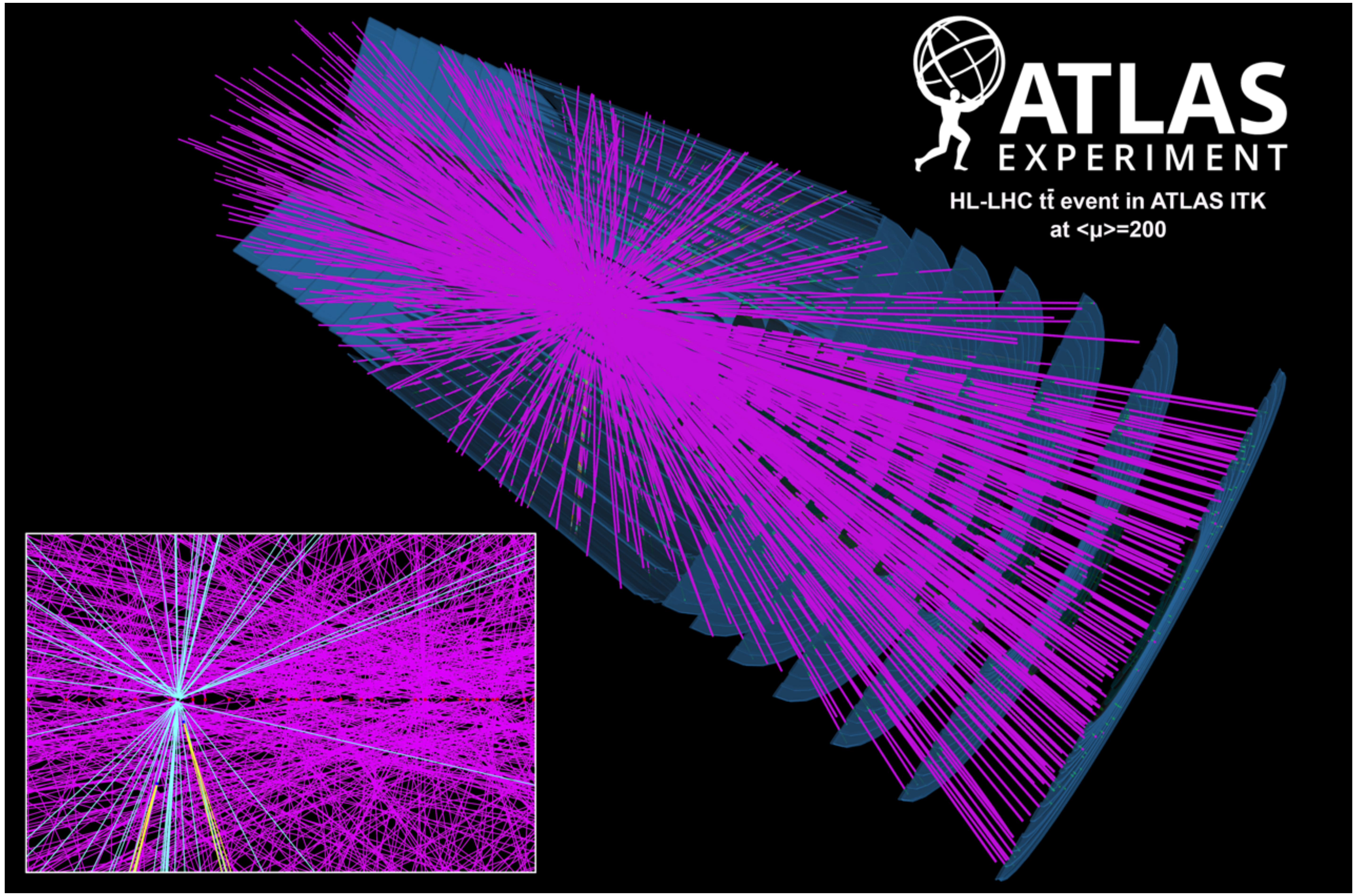
## Coming up about 2027



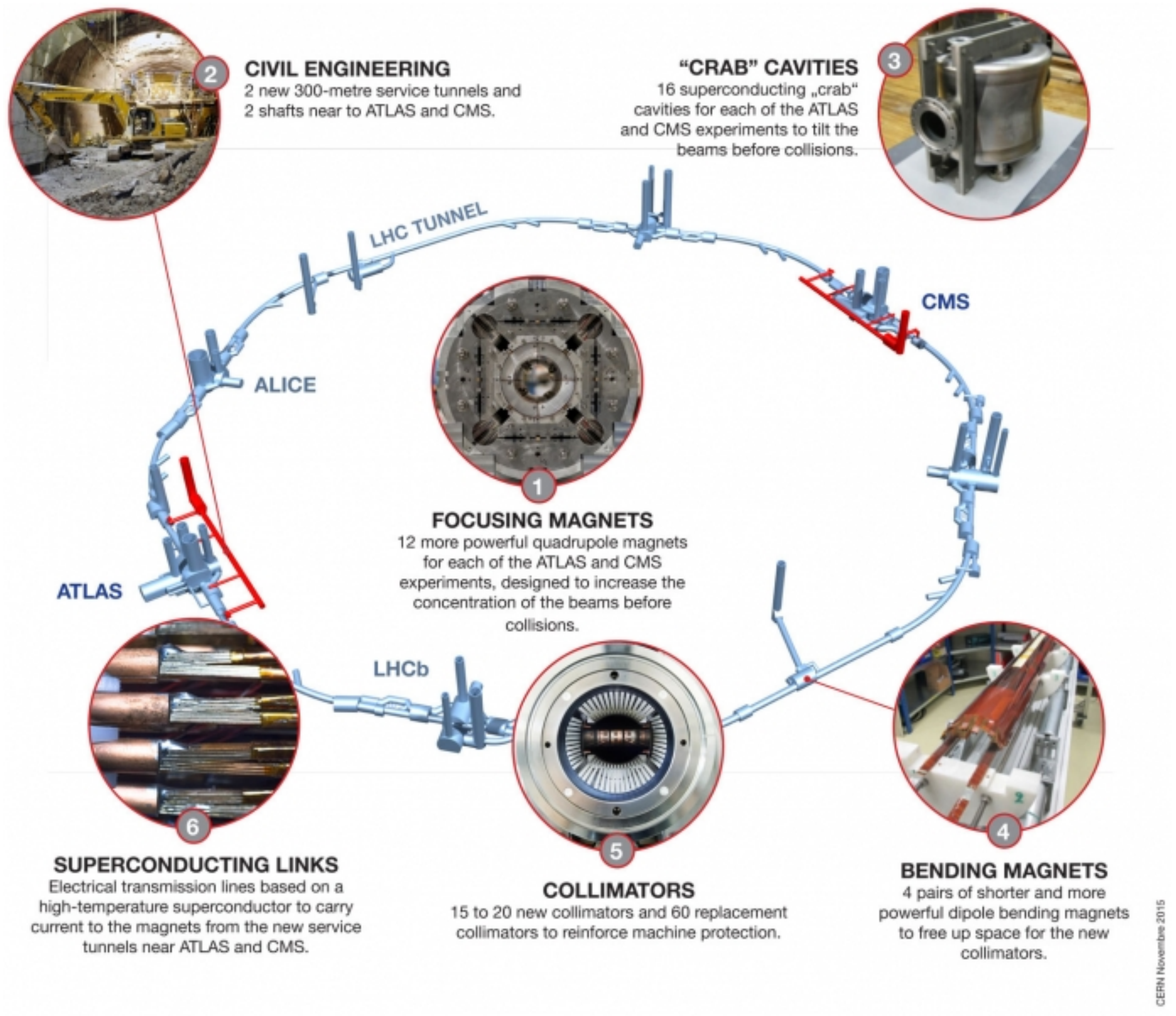
# How does a HL-LHC collision look like?

## Short answer: BUSY

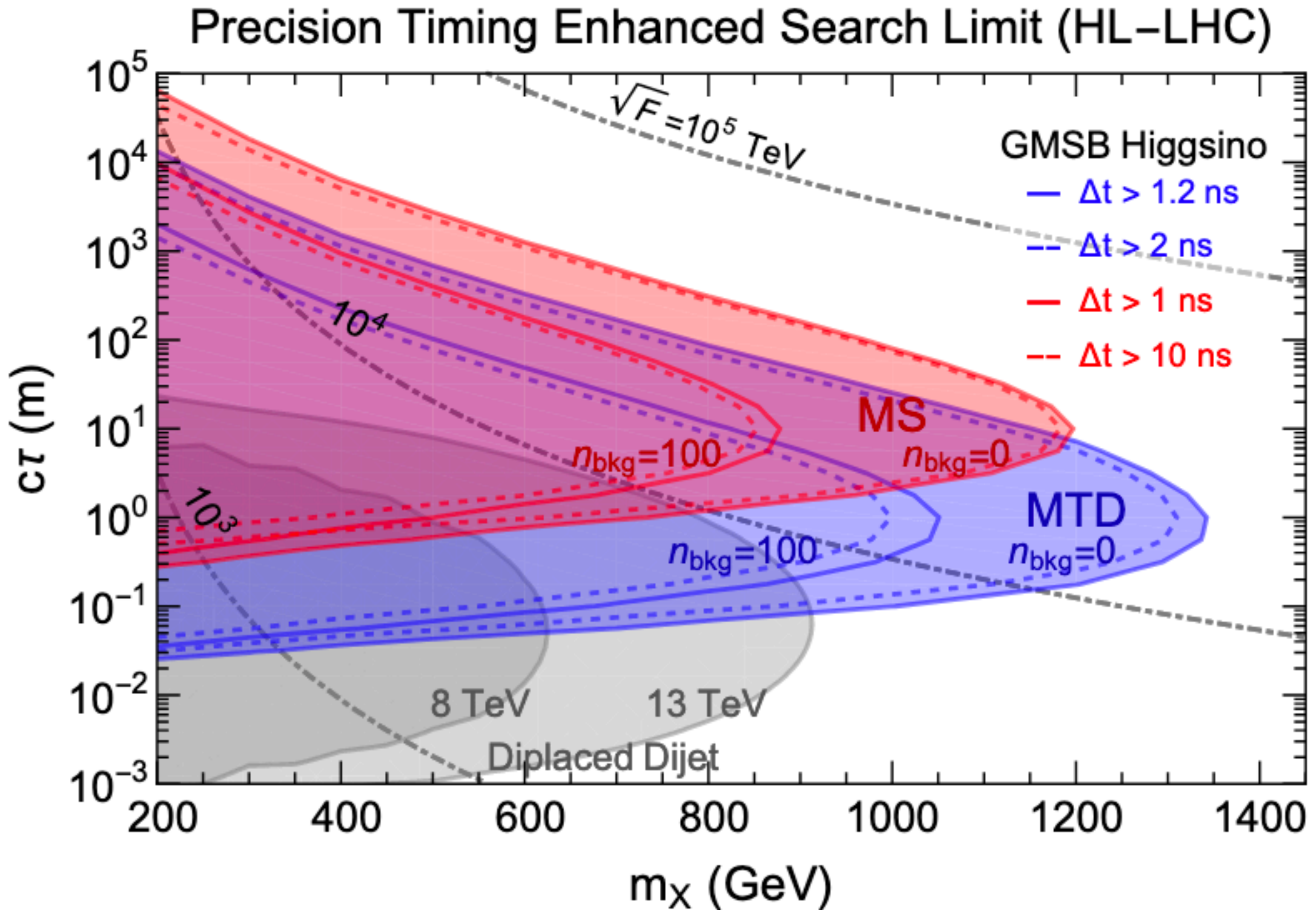
- Very high pile-up, luminosity 7.5x design
    - ~200 pp collisions are expected every 25 ns
    - Vs ~36-37 in Run-2
- Neither track reconstruction or trigger are going to get any easier



# HL-LHC for long-lived particles




HiLumi HL-LHC PROJECT

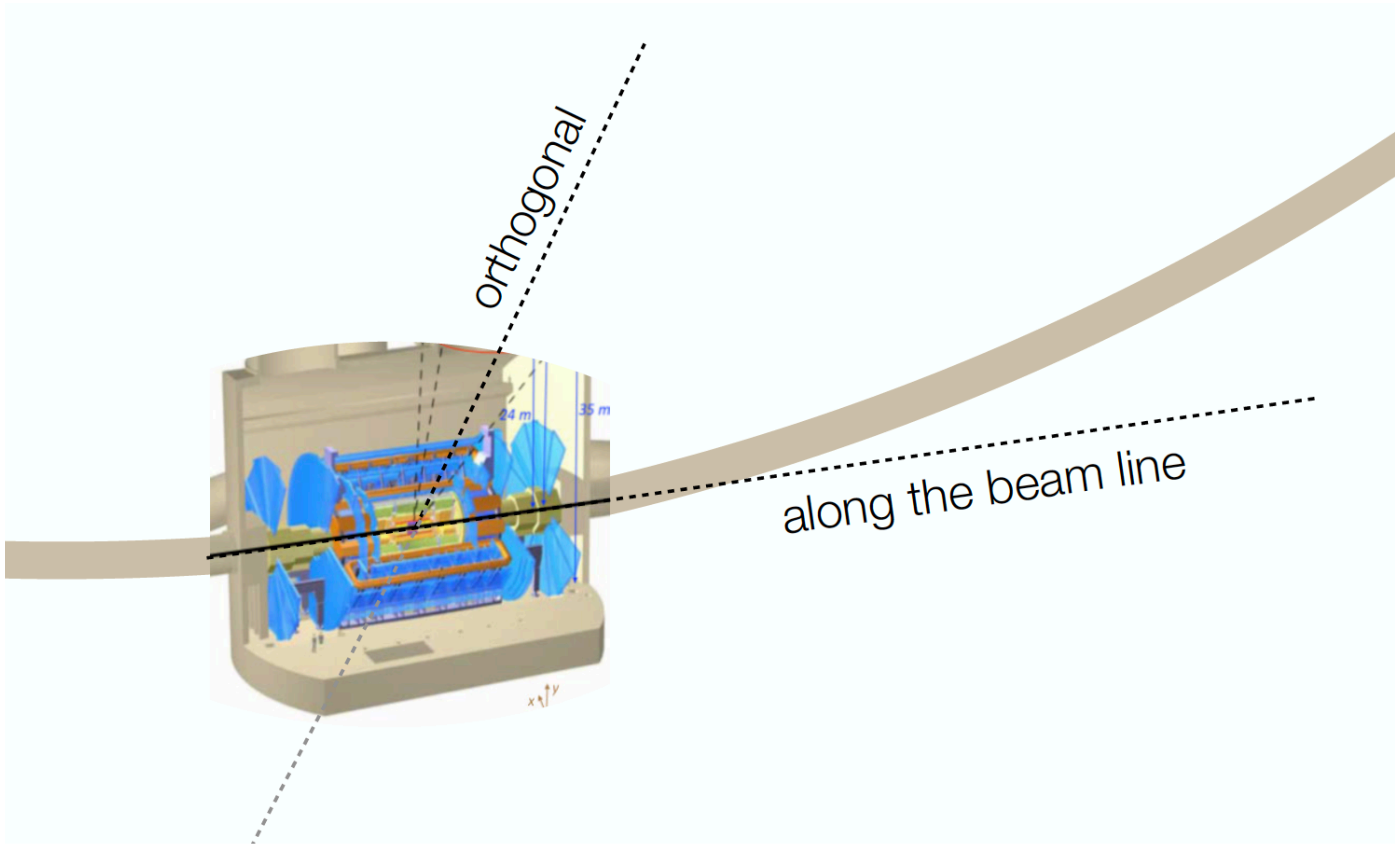



- New functionalities
  - **Track triggers** (arXiv:1907.09846): e.g. trigger on displaced muons from the same vertex to find dark photons (arXiv:1705.04321)
  - Better **timing information**: using timing information to target pair-produced LLPs significantly delayed (arXiv:1805.05957)

# HL-LHC opens the door to something else

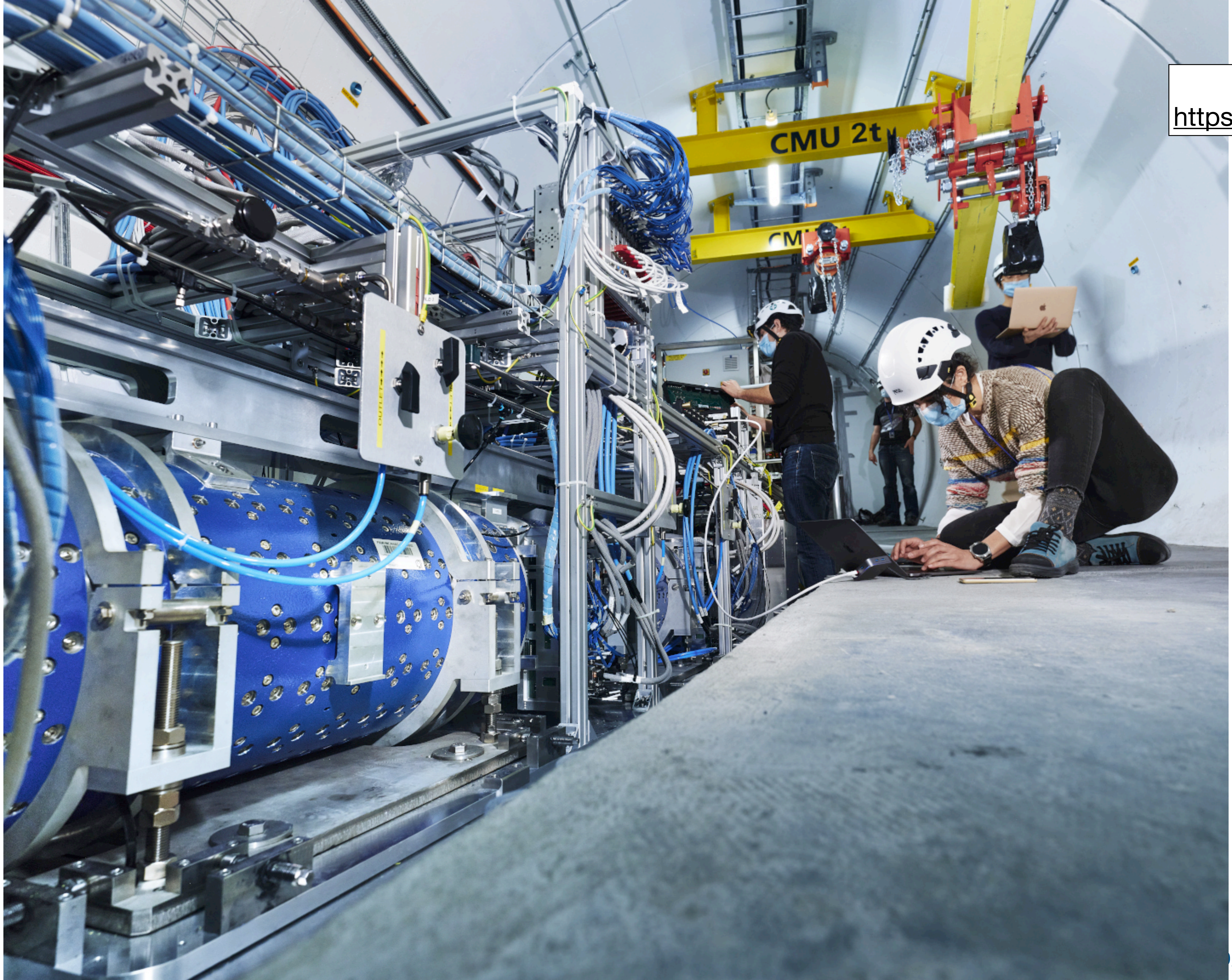
## When even ATLAS is not big enough

- Some long-lived particles could be long enough to decay outside the LHC detectors
- And in fact not even ATLAS is big enough cover the whole lifetime  gap
- We can supplement them with external detectors
    - Would catch very long decay lengths and more importantly: will have little background



# HL-LHC: Dedicated experiments

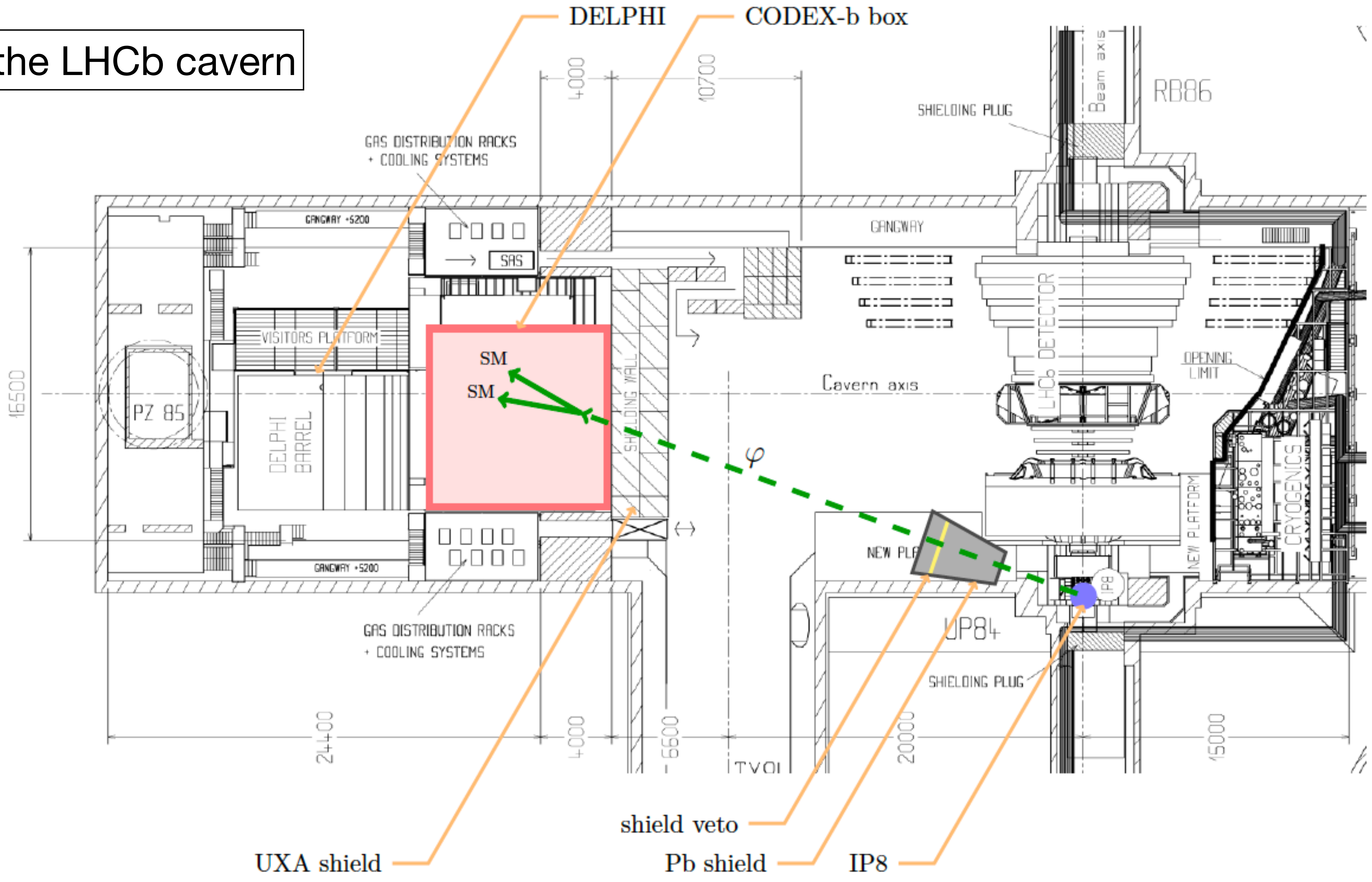
- Complementary instrumentation in the caverns offering low background environments
  - FASER: (approved) ~1 $m^3$ 480 m downstream from the ATLAS interaction point (on-axis)
  - MATHUSLA: (proposed) large-scale surface detector instrumenting ~$8\times10^5 m^3$ above ATLAS or CMS (off-axis)
  - CODEX-b: (proposed) ~$10^3 m^3$ detector in the LHCb cavern (off-axis)
  - AL3X: (proposed) cylindrical~900 $m^3$ detector inside the L3 magnet and the time-projection chamber of the ALICE experiment
  - ANUBIS: (proposed) $1\times1$ $m^2$ units on top of ATLAS/CMS (off-axis)




FASER installation this spring
https://cds.cern.ch/record/2756507?ln=en

21)

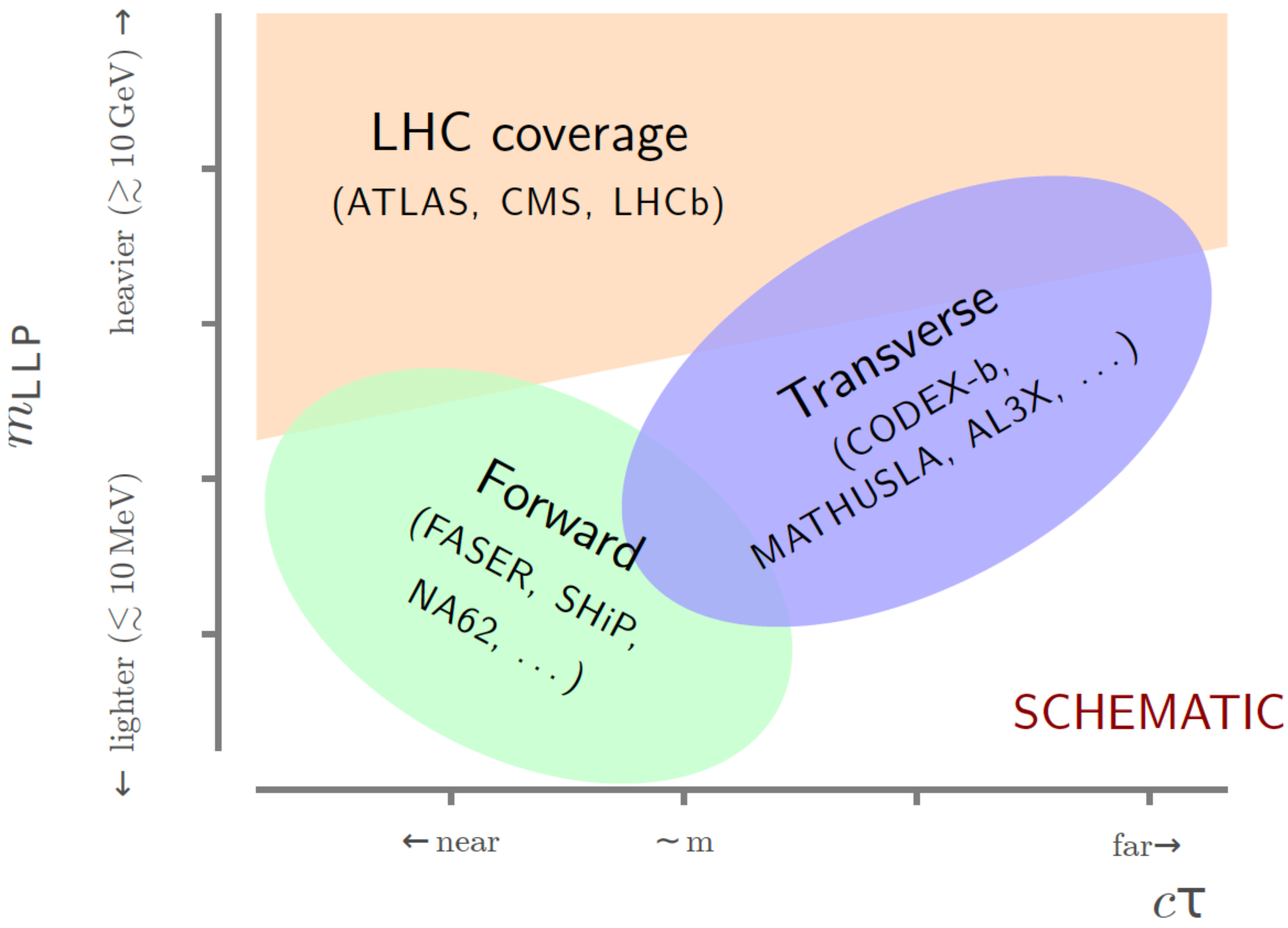
Plan of CODEX-b in the LHCb cavern



# More LLP experiments

- Beam-dump experiments:
  - **SHiP:** (proposed) would require dedicated operation with the 400 GeV SPS beam

- Experiments for exotic electromagnetic charge:
  - **MilliQan:** (demonstrator taking data) searching for millicharged particles in the drainage gallery of CMS
  - **MoEDAL:** (running) looking for highly ionizing particles like magnetic monopoles at LHCb alongside MAPP

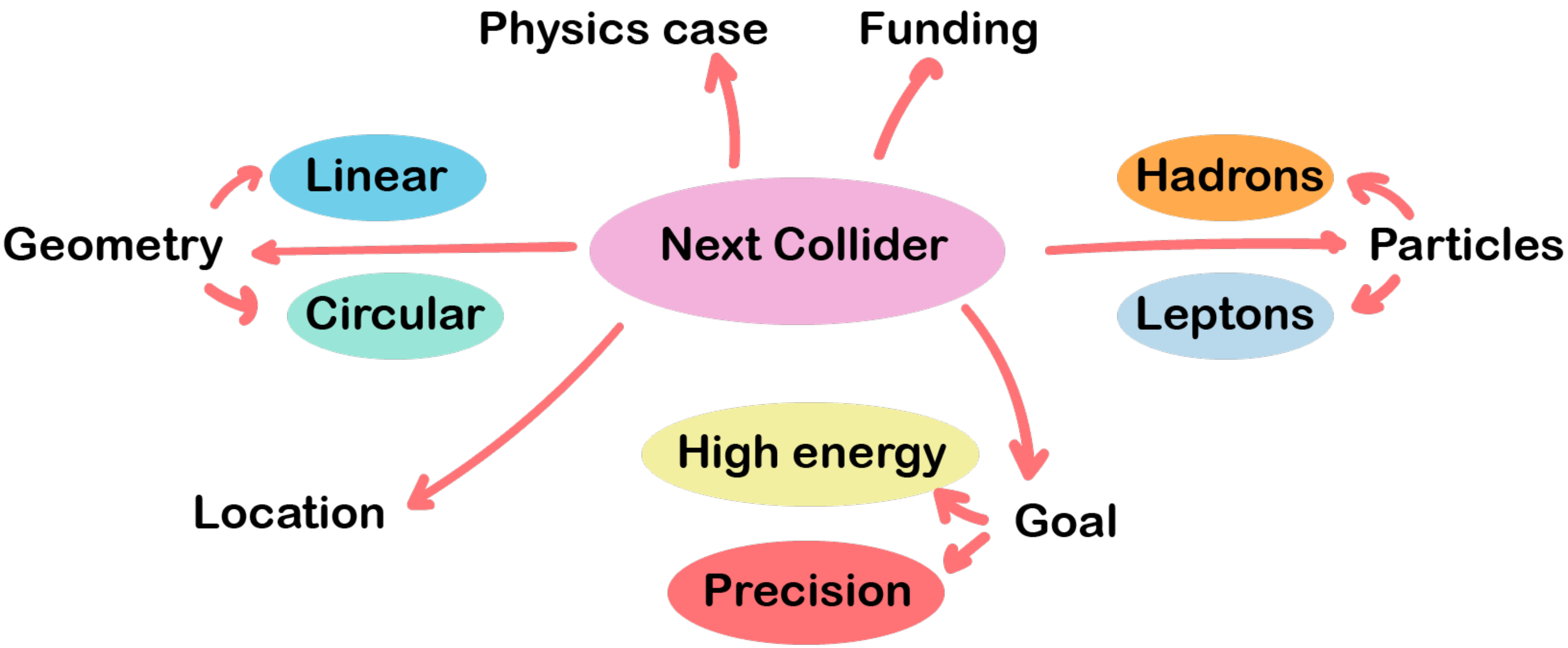



- ATLAS/CMS upgrades for the HL-LHC will provide new functionalities
- External detectors off and on-axis could extend the LLP reach
- Beam bump experiments could extend the search for low-mass models

# And then?

# We do not know

**yet**

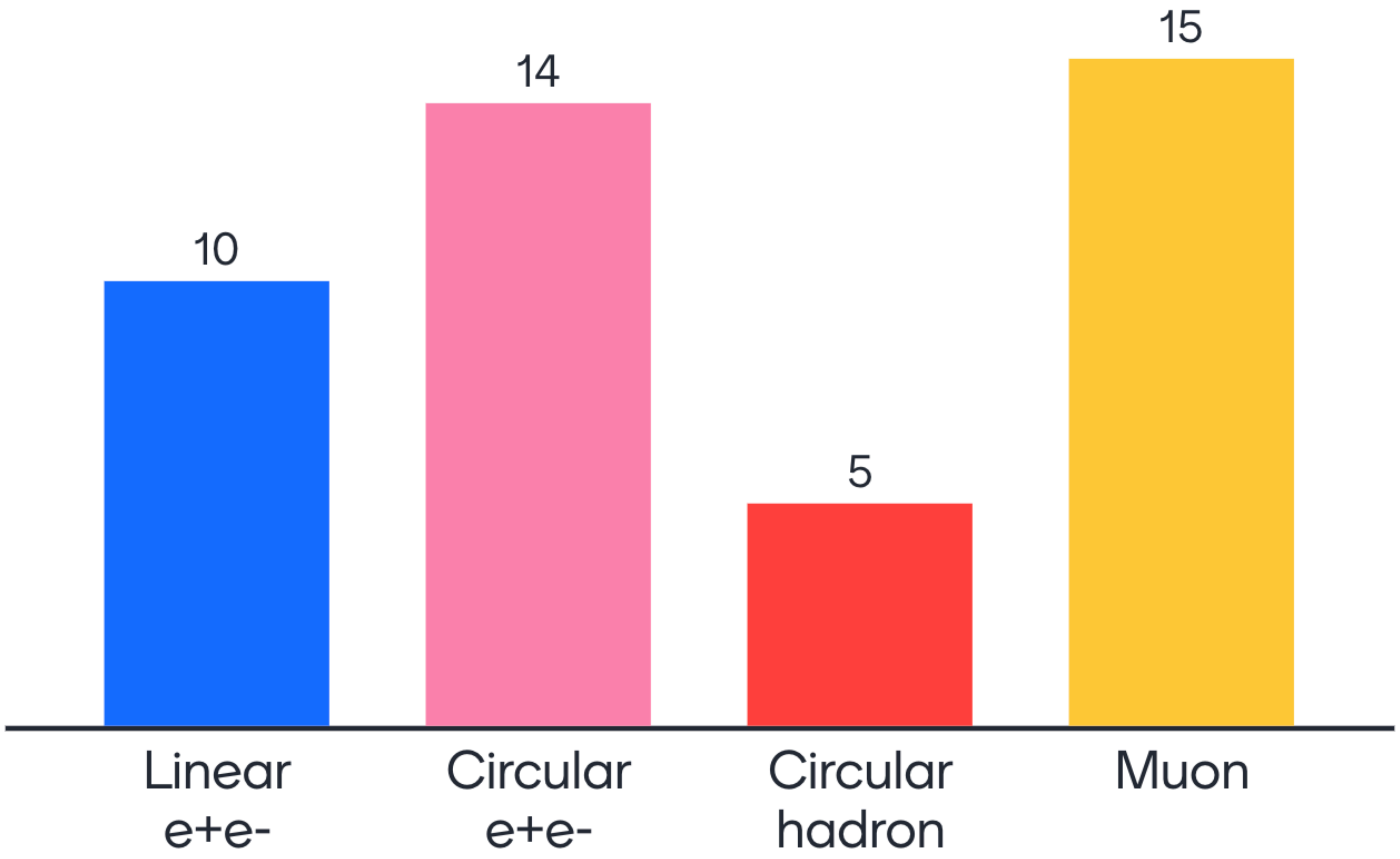


# Quiz stop #3!

Go to **www.menti.com** and use the code

# What future collider would you go for?

Mentimeter

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# The European Strategy for Particle Physics

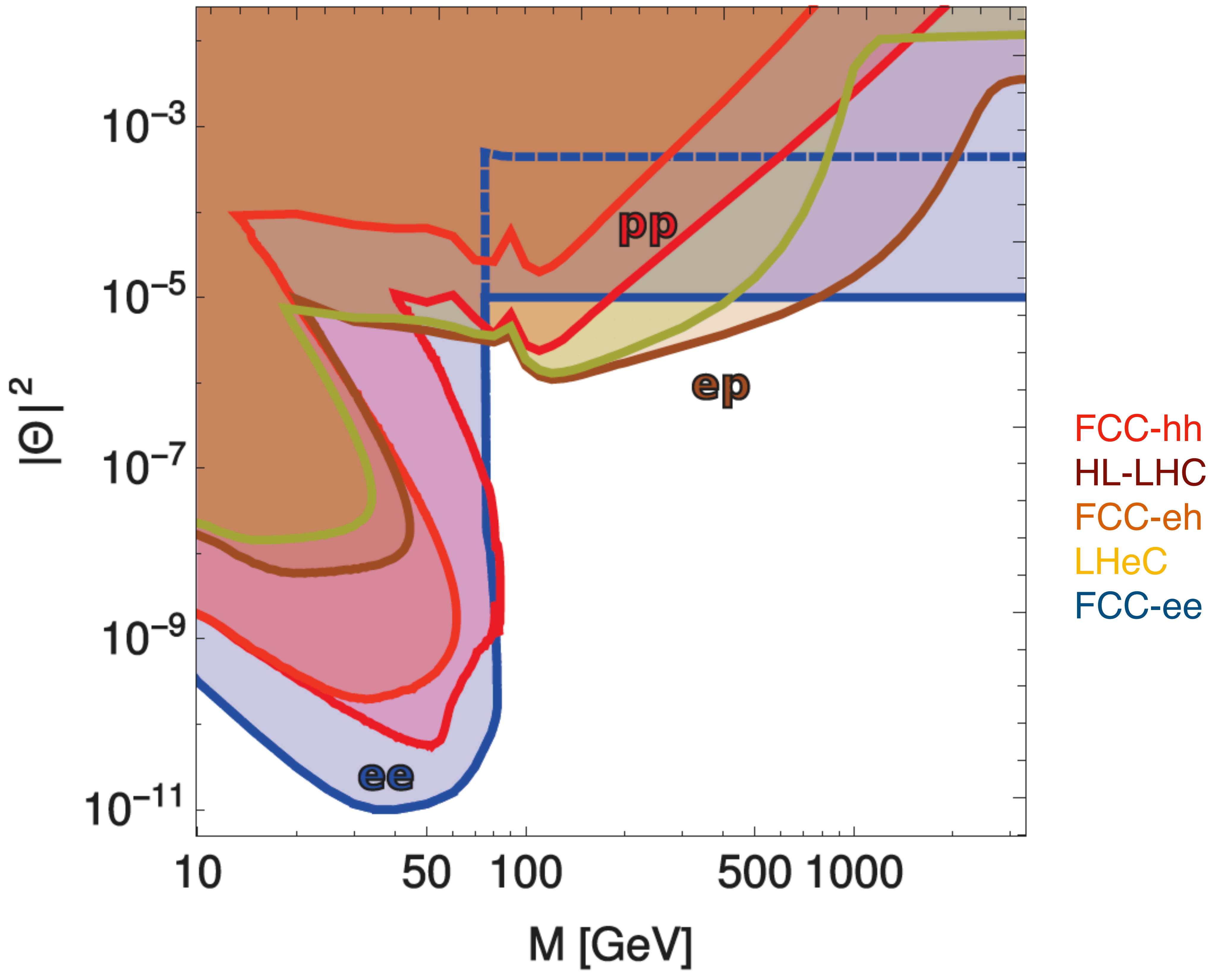
## 2020 Update

- *“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 […]”*

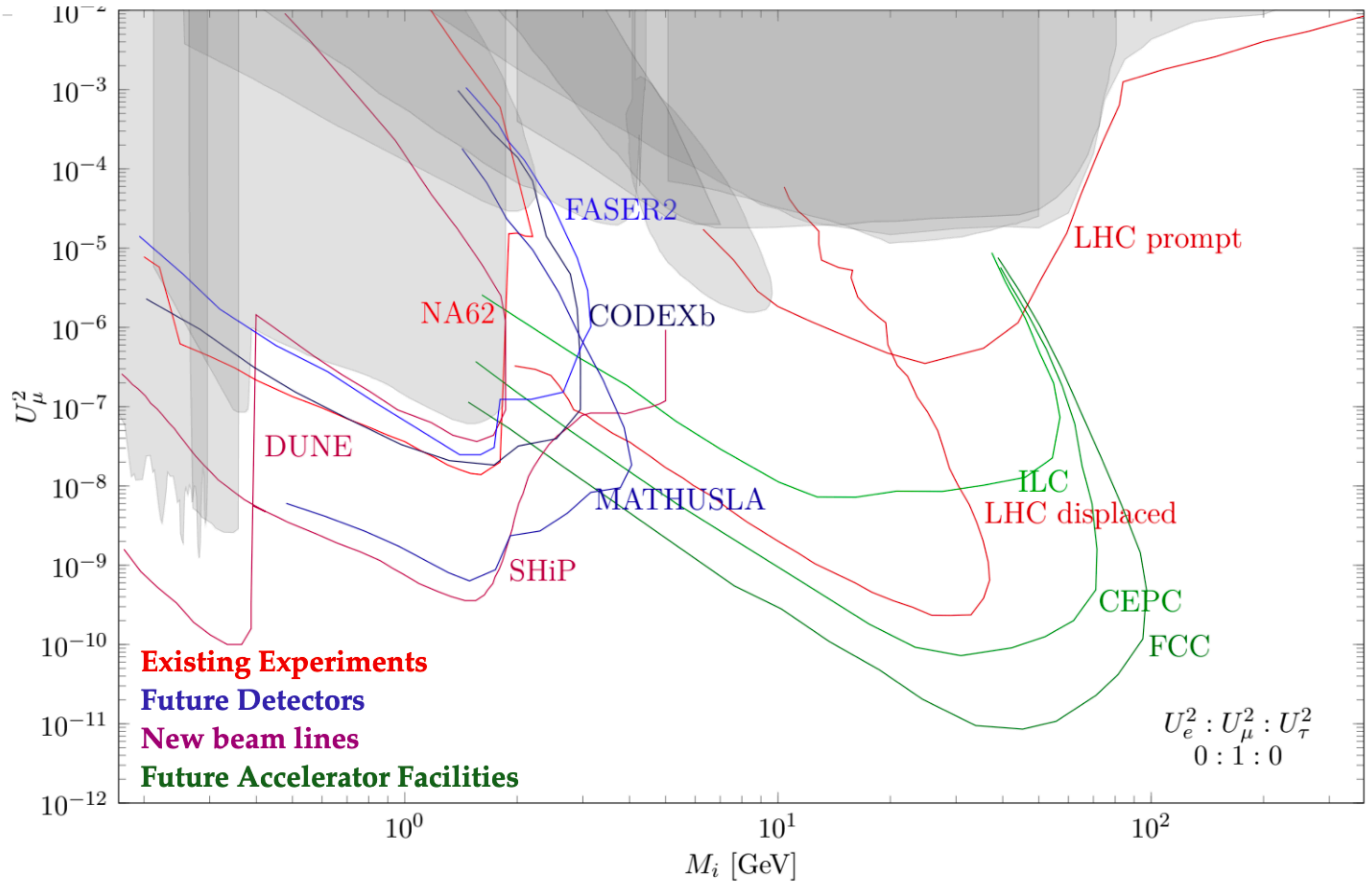
# An e+e- circular collider could be fantastic for LLP

## Especially for HNL

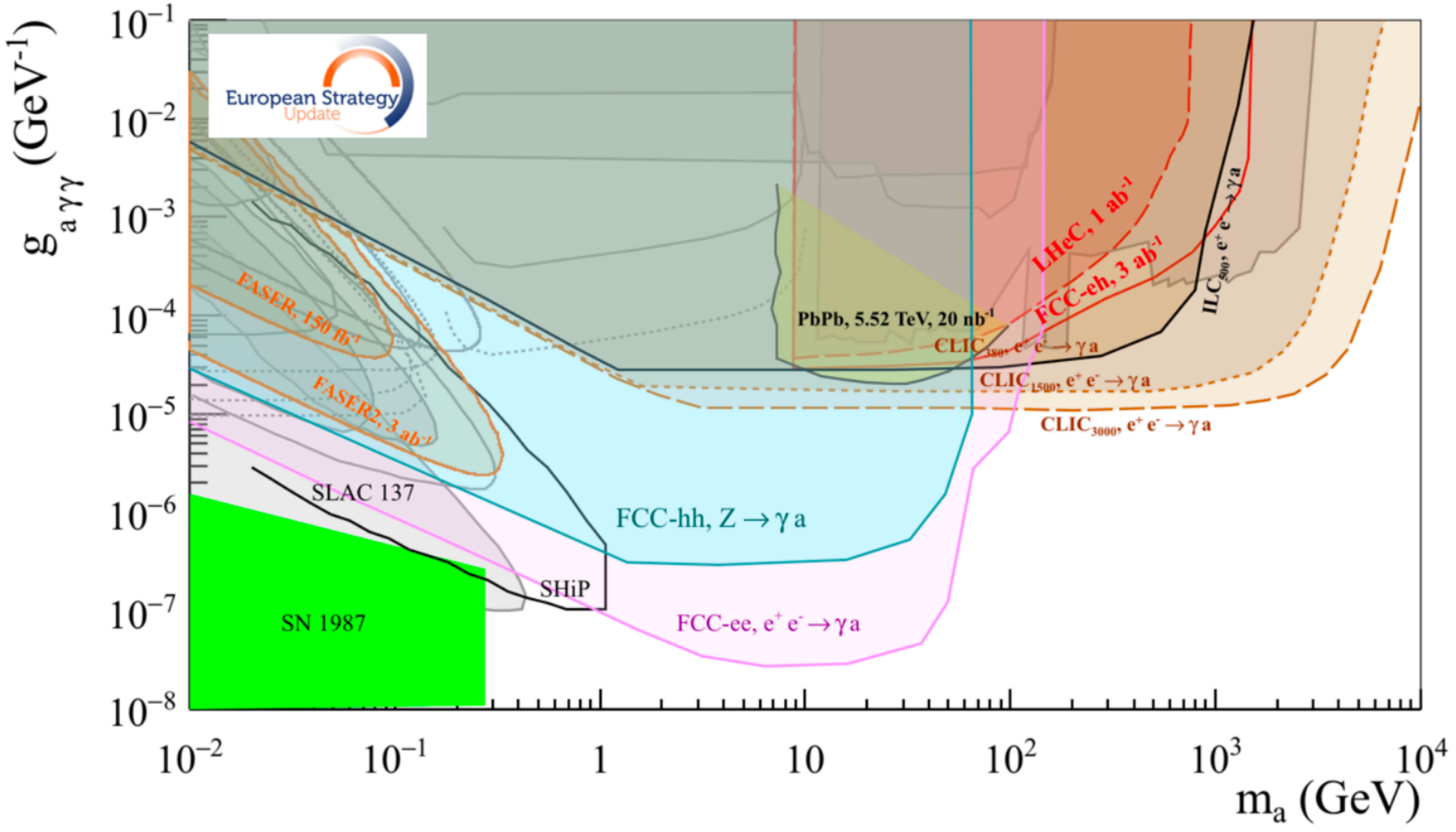
arXiv:1612.02728




Marco Drewes (FCC-ee LLP informal team)



# Complementarity

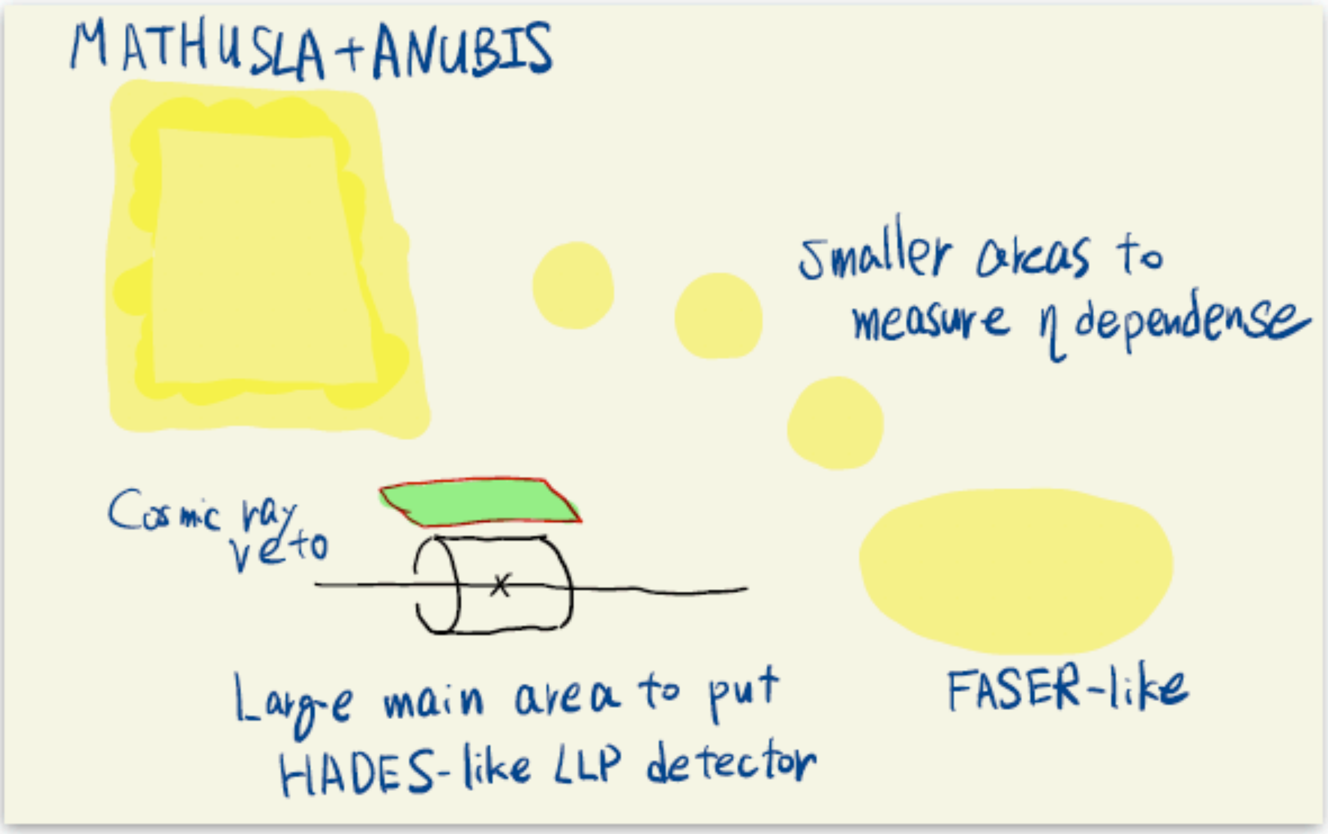


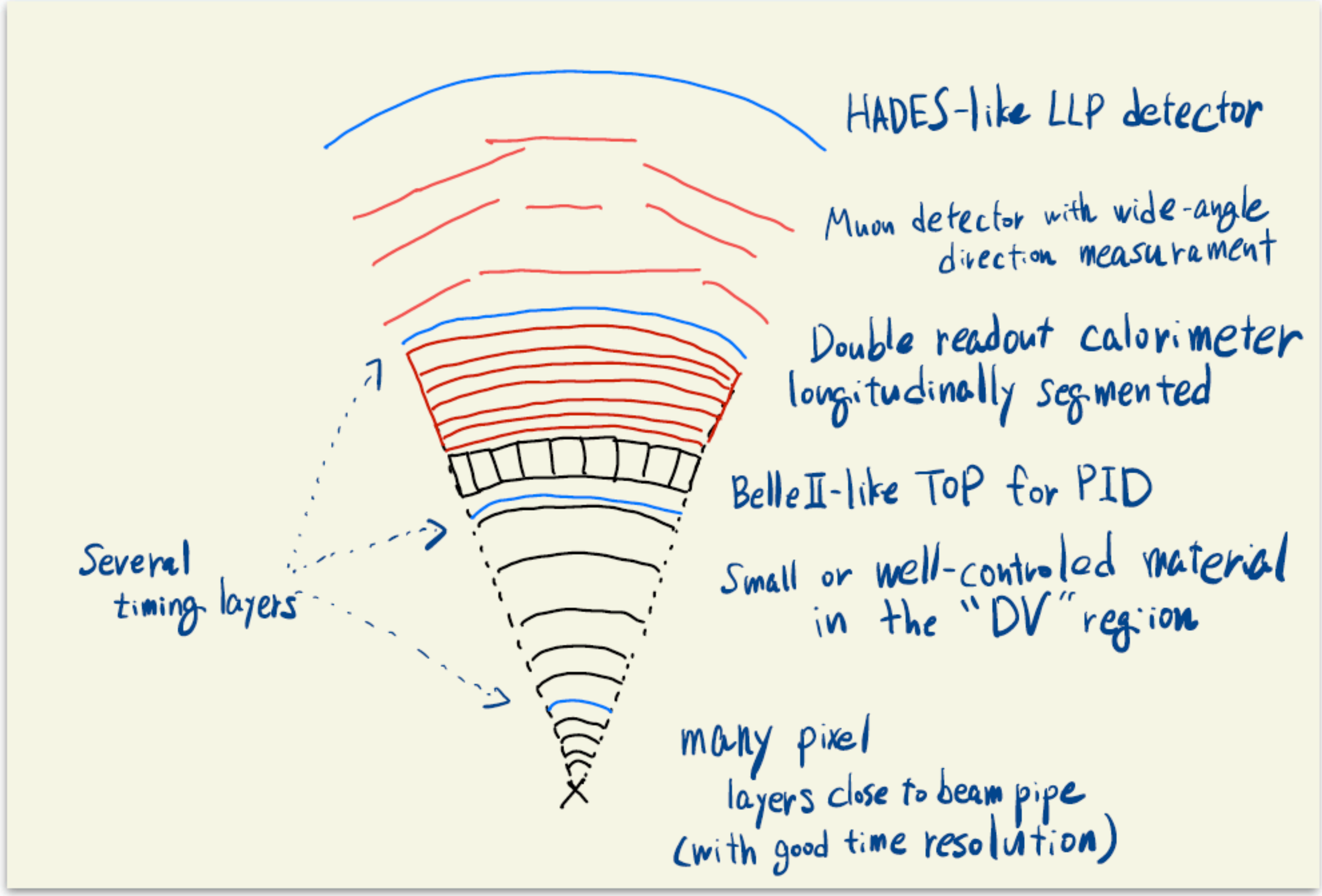

Exclusion limits for ALPs coupled to photons. All curves correspond to 90% CLexclusion limits, except for LHeC/FCC-eh (95% CL exclusion limits), FCC-ee (observation offour signal events) and FCC-hh (observation of 100 signal events). From the Briefing Book

- Different colliders offer sensitivity to different parameters in different models
  - The key word is **complementarity**
- Certain colliders offer higher energy, other cleaner environments, access to different ranges of mass/couplings
  - **Many challenges related to LLP will be common**

Ryu Sawada

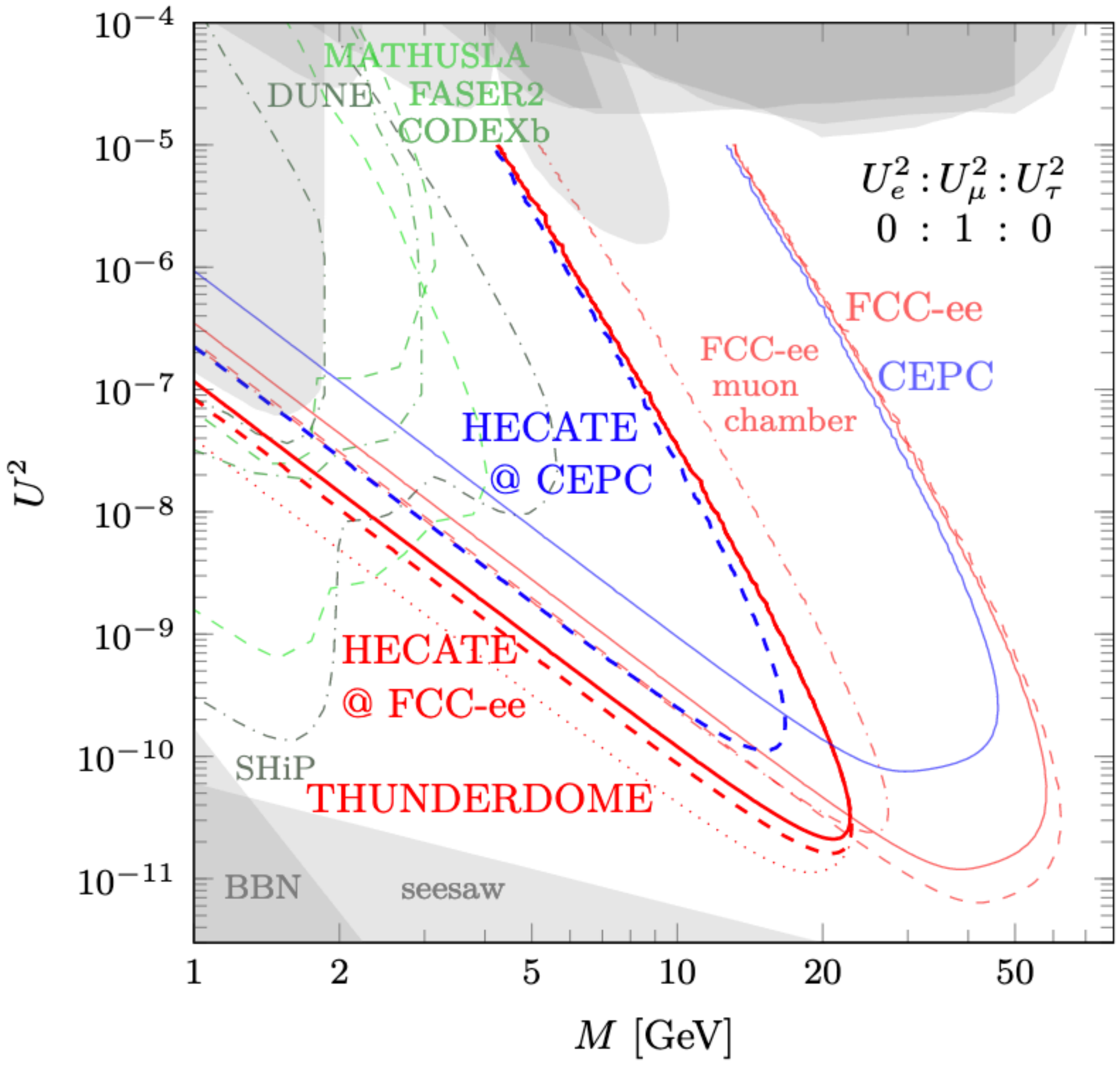
# A dream LLP detector?




Time to incorporate LLP to the design of the future collider Experiments!

Including additional experiments!
e.g. FCC-ee/CepC Mathusla-like concept HECATE: arXiv:2011.01005

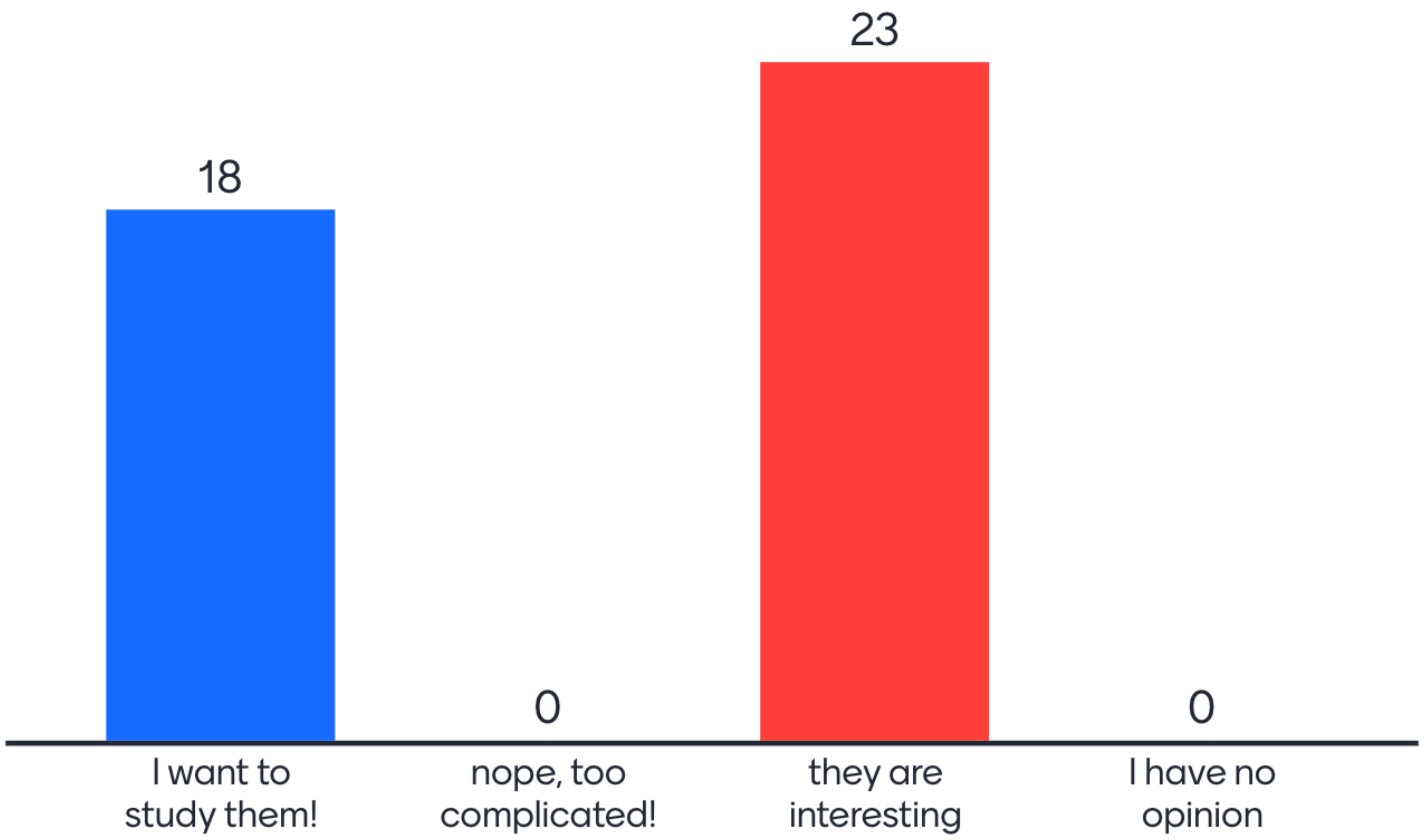


# FINAL Quiz!

Go to **www.menti.com** and use the code **5699 5724**

# What do you think of long-lived particles now?

Mentimeter

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# Summary

- LLP searches are a very attractive alternative (and complement) to mainstream new physics searches at colliders
- **There are many interesting lines to explore connected to long-lived particles**
  - **Very much relevant to dark matter and hidden sector searches**
    - Heavy Neutral Leptons, Hidden sectors, exotic Higgs decays…
- **Experimentally, this searches are extremely challenging and fun**
  - But challenge conventional reconstruction and trigger methods
  - An opportunity to think **out-of-the-box**
- We are currently deciding on the next particle collider after the LHC
  - The HL-LHC upgrade of the LHC already will provide new opportunities
- LLP studies then and beyond will still require custom detector design, reconstruction algorithms, triggers

# Discussion session today

## 17:30 (Lund time)

- Join Monica and I together with a group of invited experts for a discussion on a few specific analyses
- Have your questions ready!