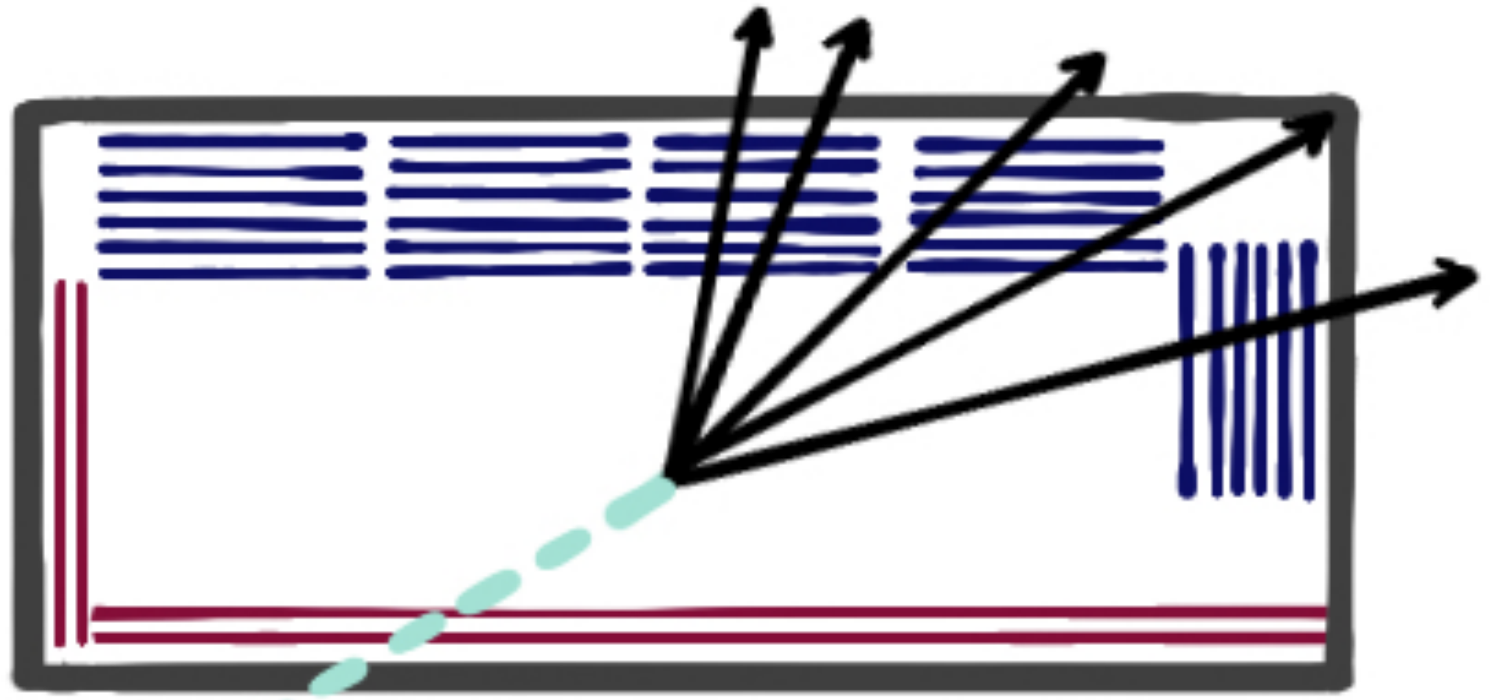
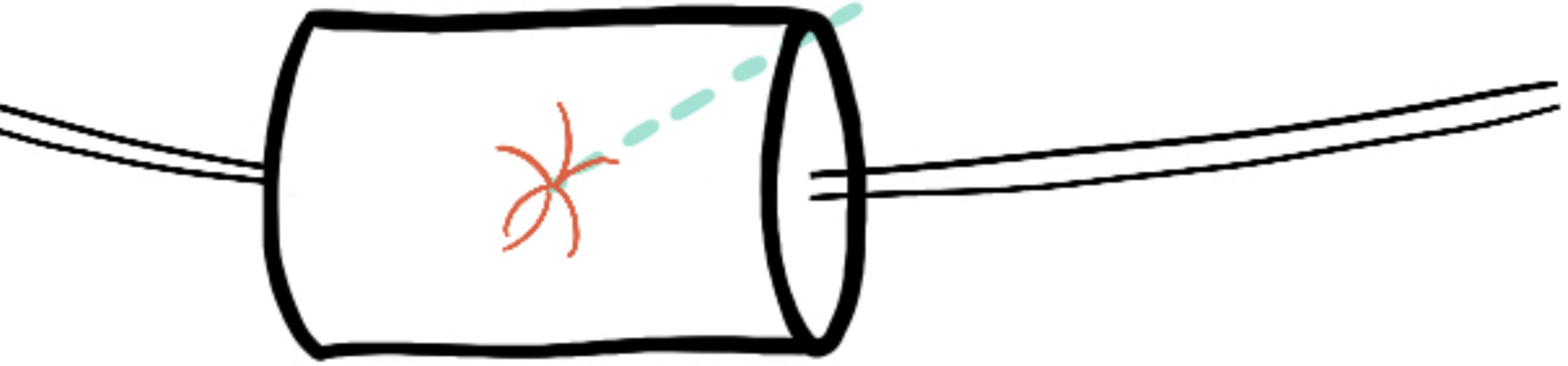


Long-lived particle detectors at the (HL-)LHC and beyond

Heather Russell (she/her), University of Victoria

CAP PPD Symposium on Future Energy Frontier Facilities

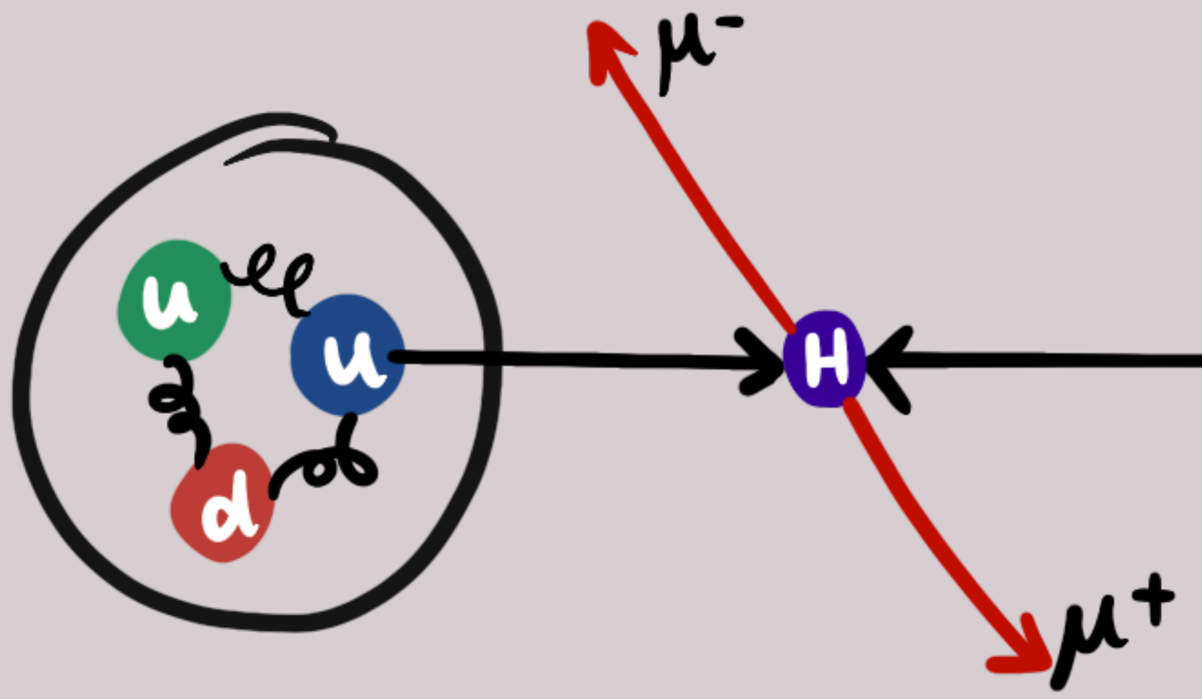
24 June 2026

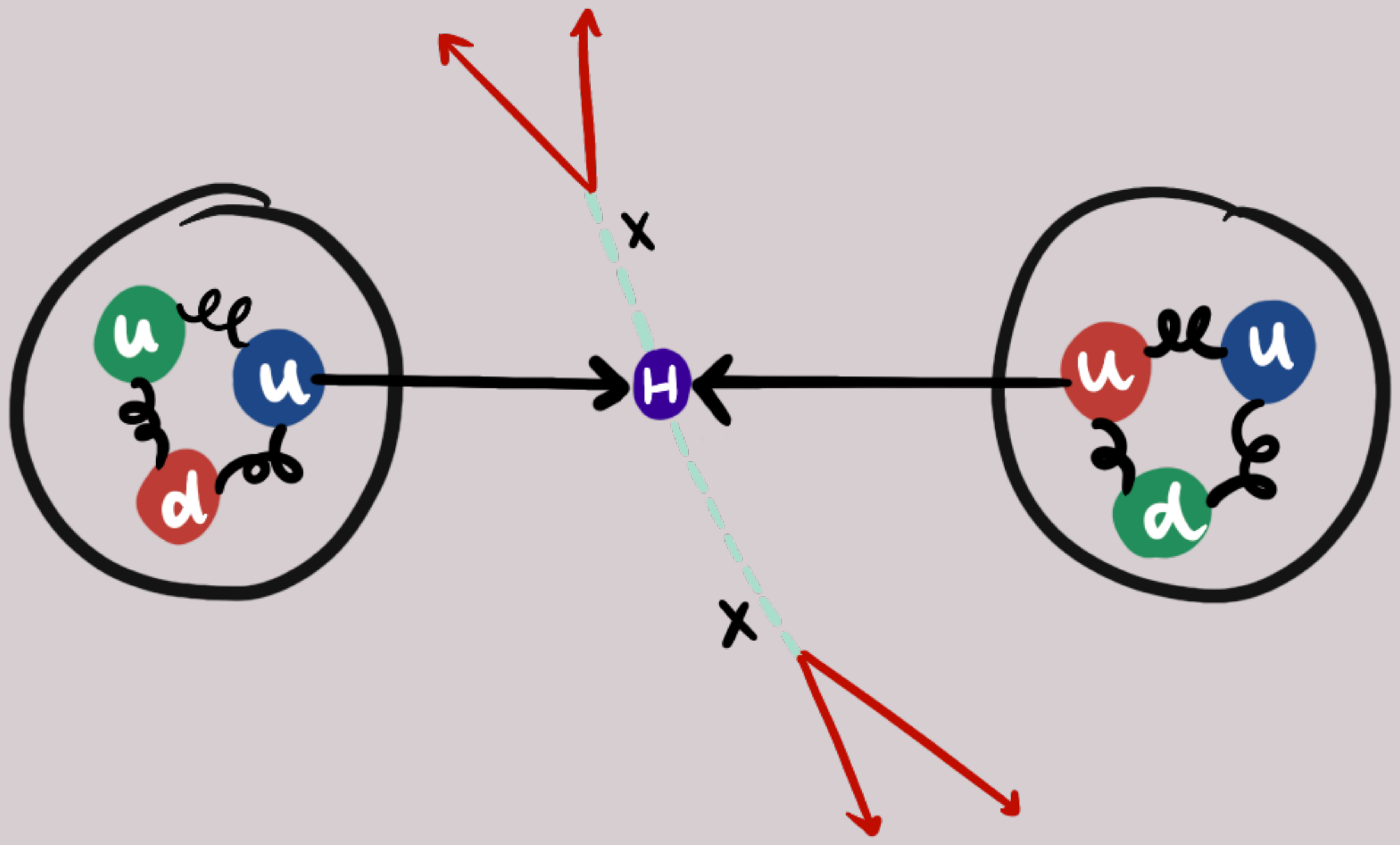


University of Victoria

Long-lived particles

(neutral) particles that decay to SM particles a **macroscopic distance** from their production location





- BSM particles in many models can be long-lived
- Their mean proper lifetime is sometimes a **free parameter** in the model and sometimes tightly constrained
- Upper lifetime constrained by big bang nucleosynthesis and the cosmic microwave background

**nothing is to scale in these sketches*

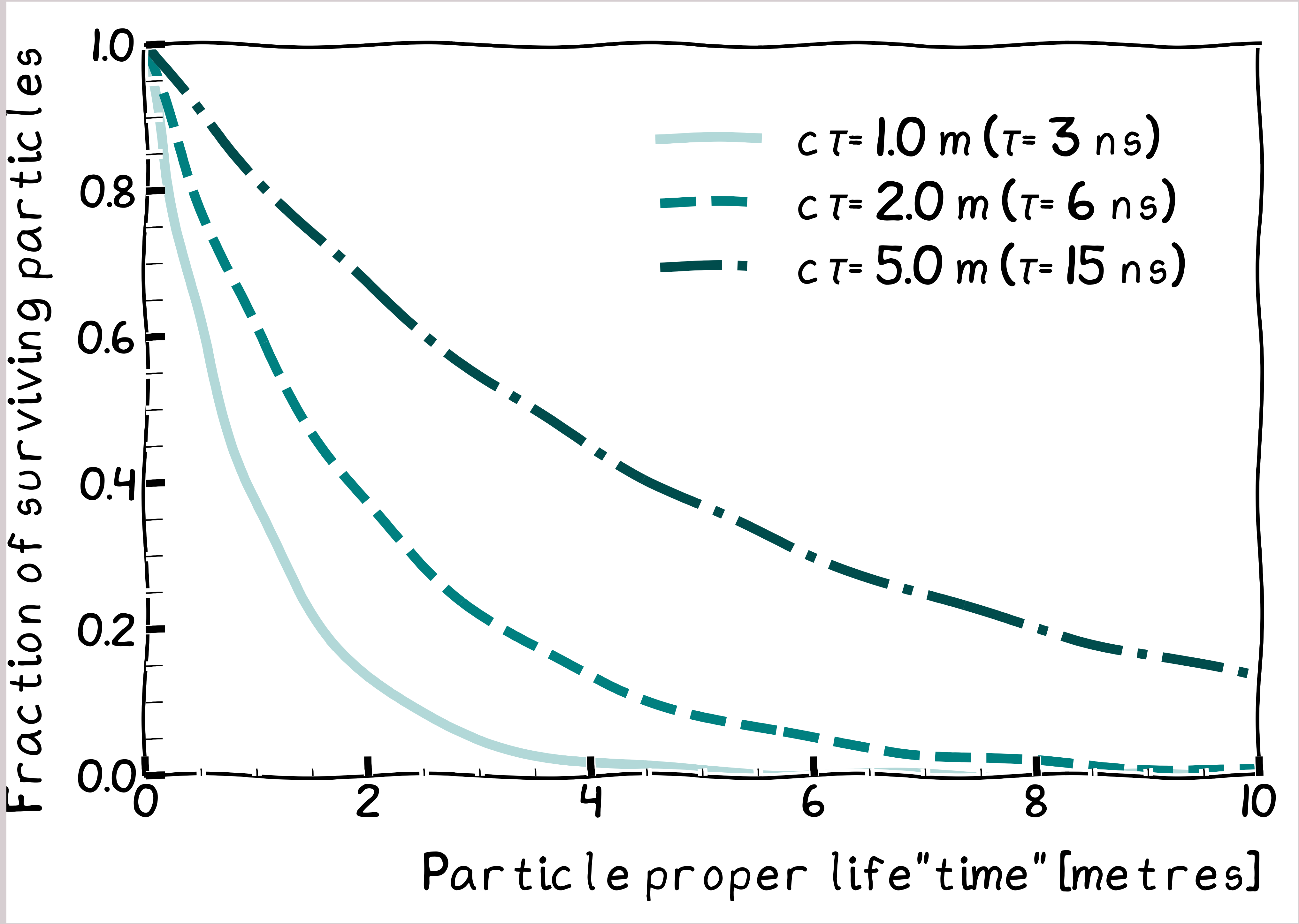
***two up quarks don't actually make a Higgs boson*

Long-lived particle decays

Each particle type has a **mean proper lifetime** $c\tau$ and will survive with a probability given by an **exponential distribution**

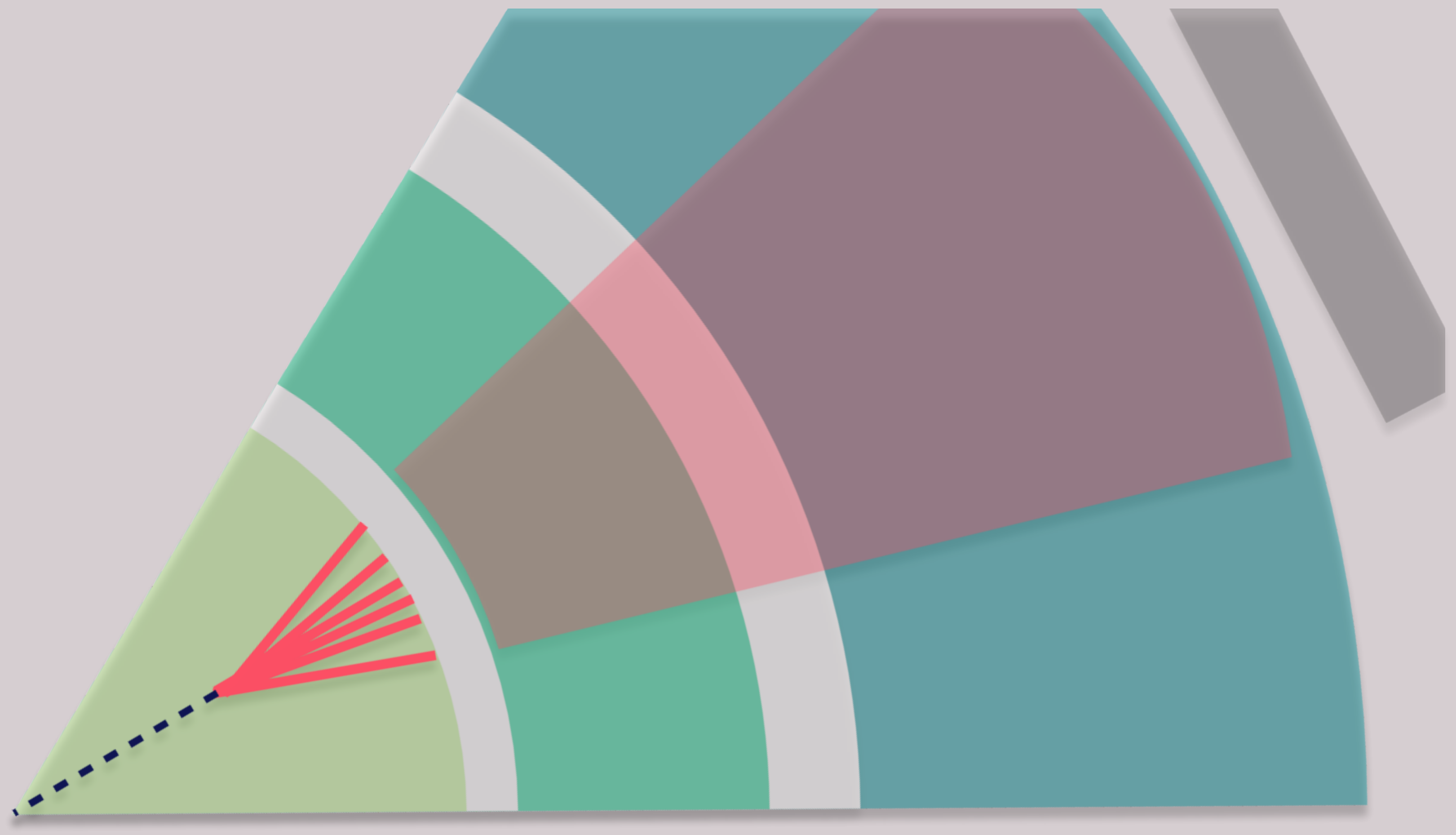
Longer mean proper lifetimes

Particles live longer before decaying



Particle **boost** affects the decay position; boost depends on the LLP production mechanism

Detector signatures vary depending on both **which particles** the LLP decays into (e.g. muons vs quarks) and **where** the LLP decays (e.g. the inner detector vs calorimeter)



Types of long-lived particles

Main classes of particles/processes studied:

(Pseudo)scalars

Higgs mixing - Inherits Yukawa coupling from H

Single LLP production in meson decays ($m_{LLP} < 5$ GeV)

Pair-production in Higgs decays (only produced @ LHC, $m_{LLP} < 62.5$ GeV)

Vectors

Dark photon/Dark Z

Drell-Yan production via kinetic mixing
Higgs pair-production

Decays like photon/Z boson

Fermions

Right-handed neutrino/heavy neutral lepton

Produced in meson or direct W/Z/h decays

Decays via W/Z/h, neutrinos in decays

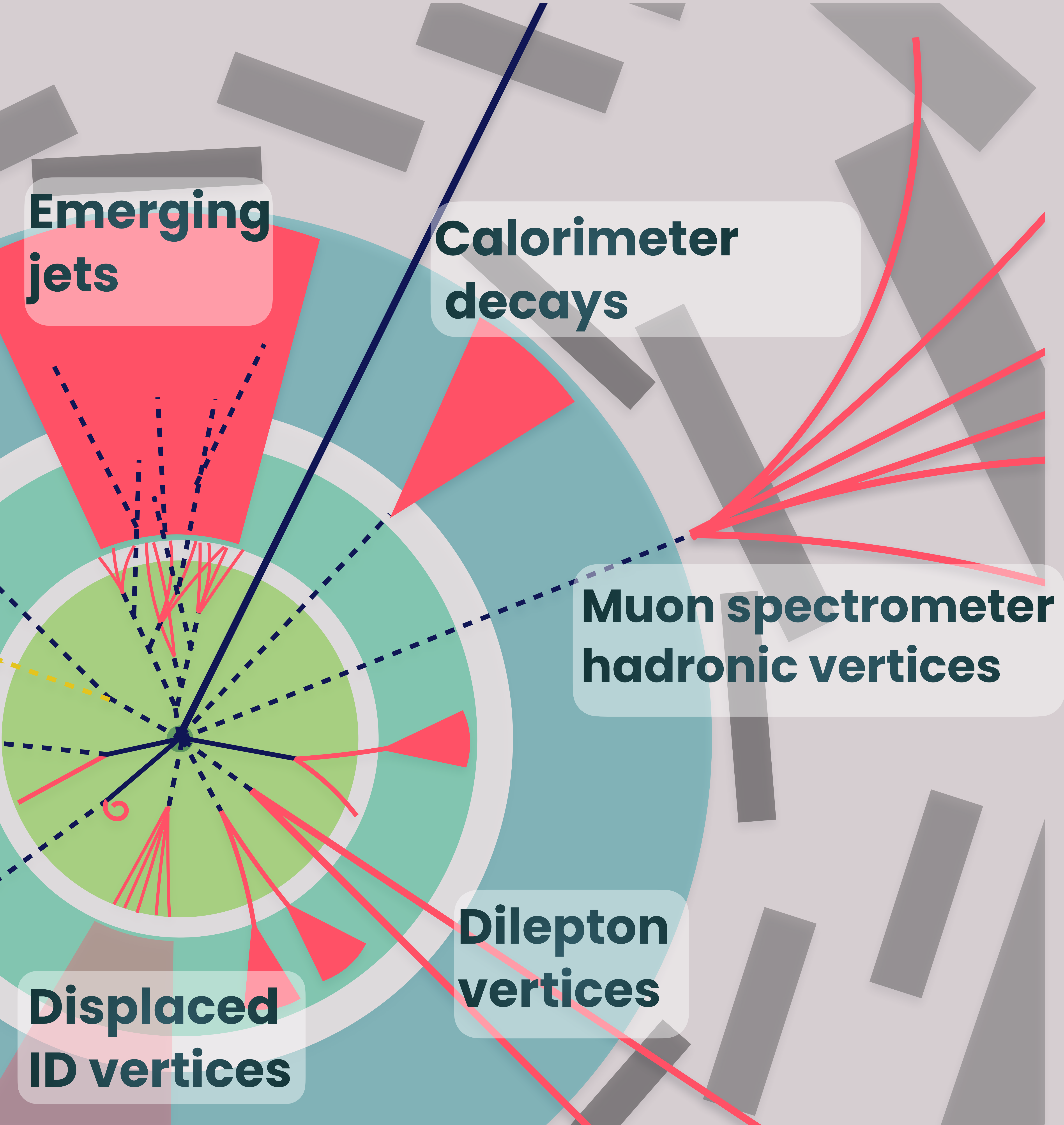
Also: RPV SUSY, axion-like particles (ALPs), more complicated hidden/dark sectors

- See e.g. arXiv:1903.04497, arXiv:2102.12143

We want to keep searches as **model-independent** as possible

- Focus on **decay topology** rather than specific model

Analyses at general-purpose experiments



Difficulties with these analyses:

- detectors were not designed to reconstruct non-prompt objects
- Trigger system was not designed to select these events and/or events look very similar to high-rate SM processes *to the trigger system*
- SM backgrounds are poorly modelled and can be high compared to expected LLP decay rates
- Detector was not designed to help distinguish these processes from SM / non-collision backgrounds

and....

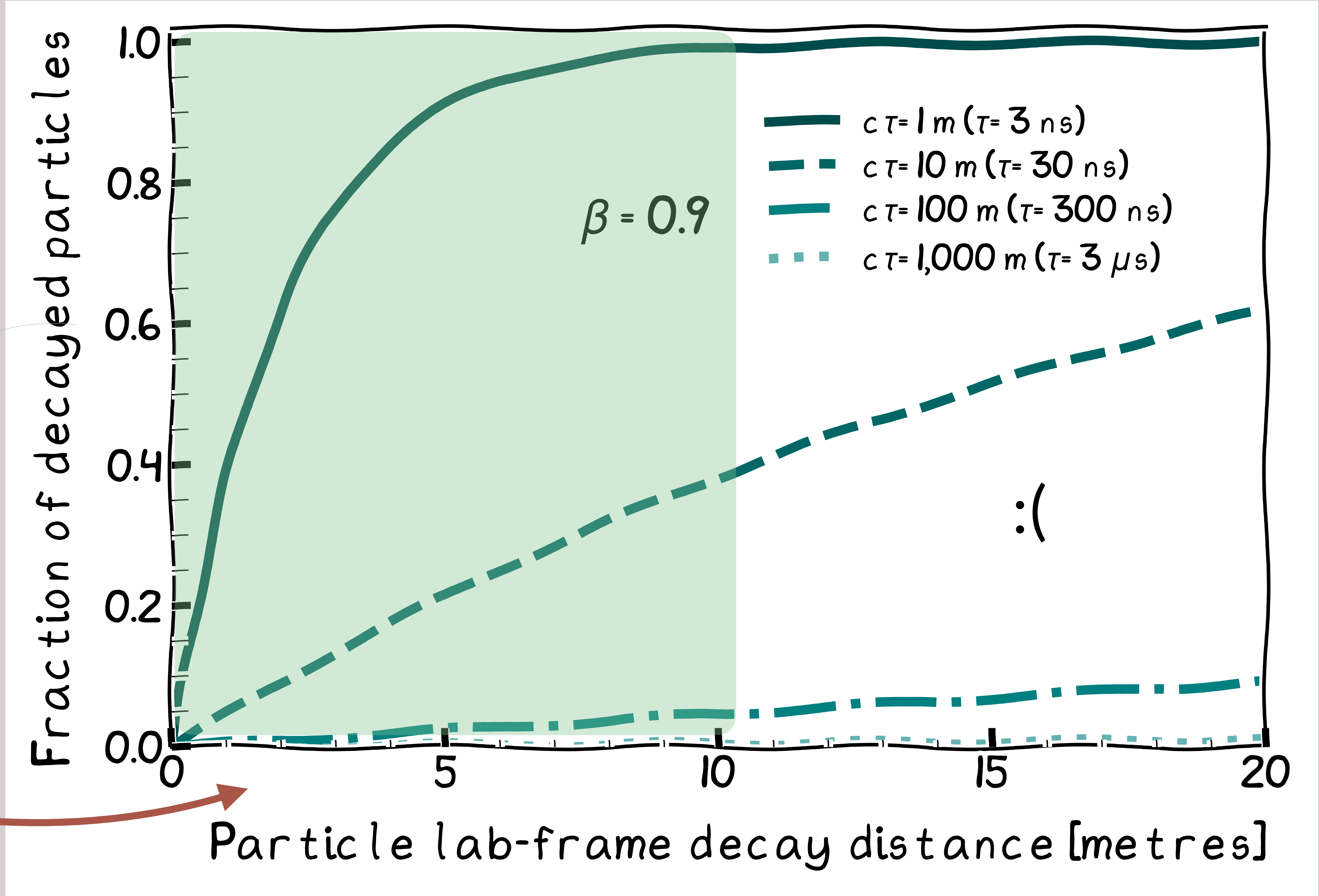
Analyses at general-purpose experiments

Standard particle detectors can detect LLPs decaying **up to about 10m**

Beyond that, they would escape detection of all existing detectors

Particles with **longer lifetimes** (smaller couplings) will not often decay inside

No decays ⇒ no discovery.



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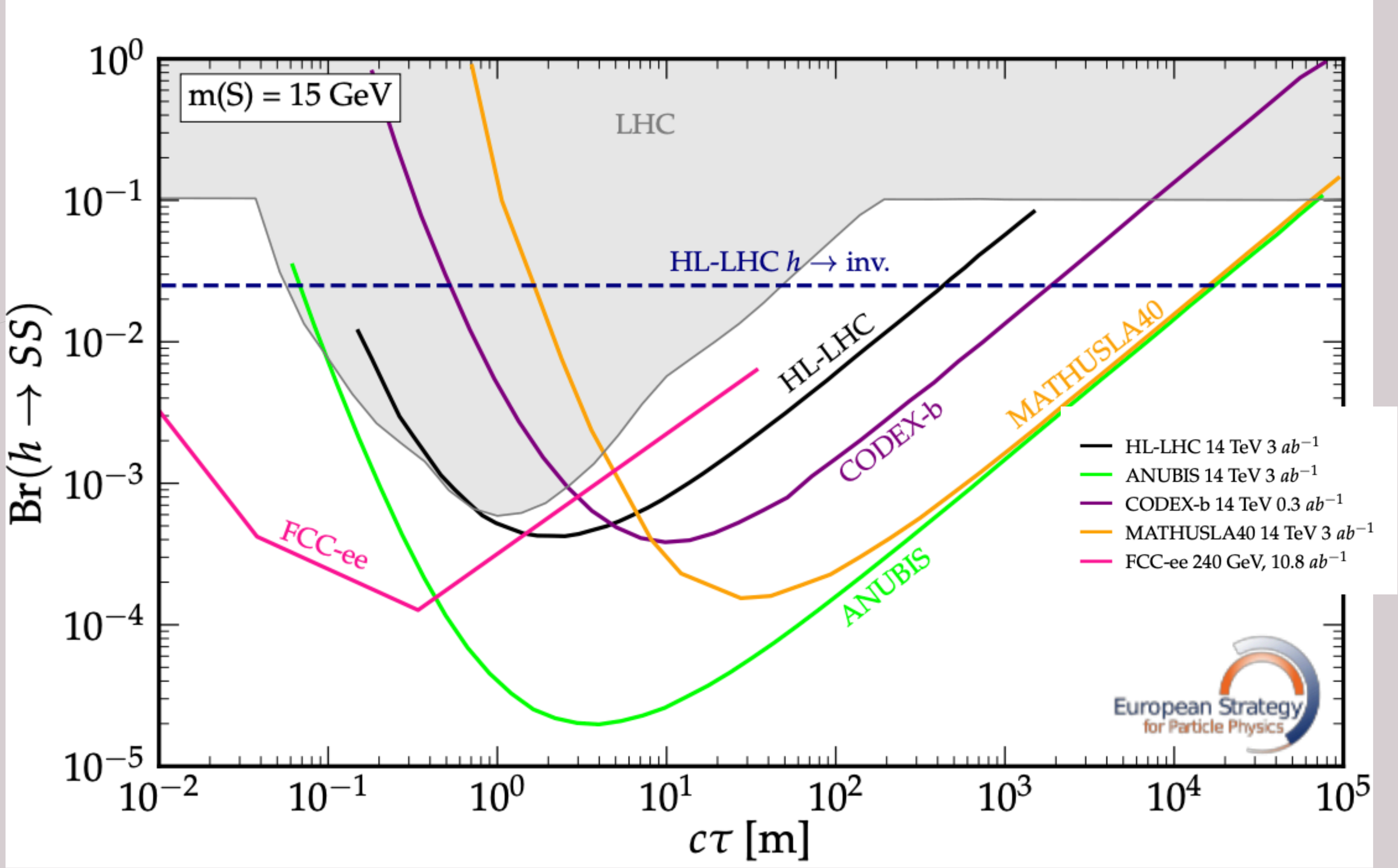
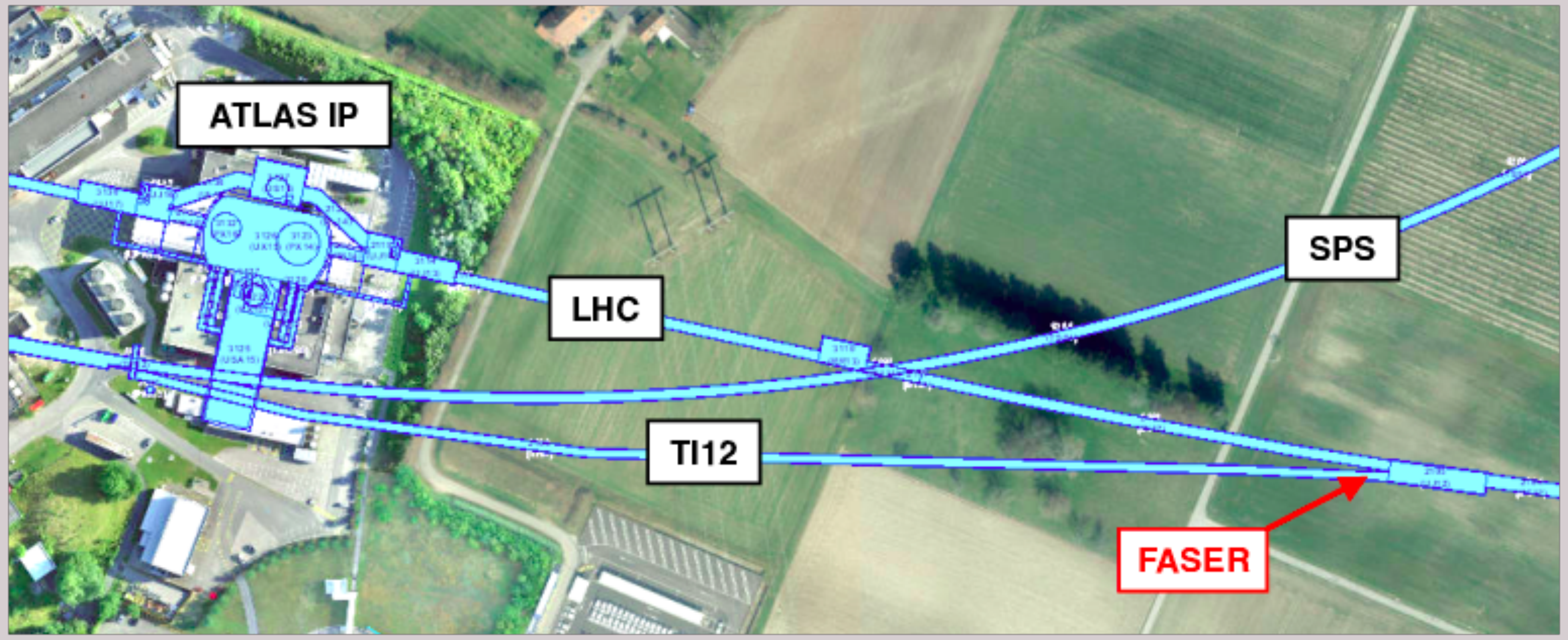


Existing auxiliary detectors

FASER

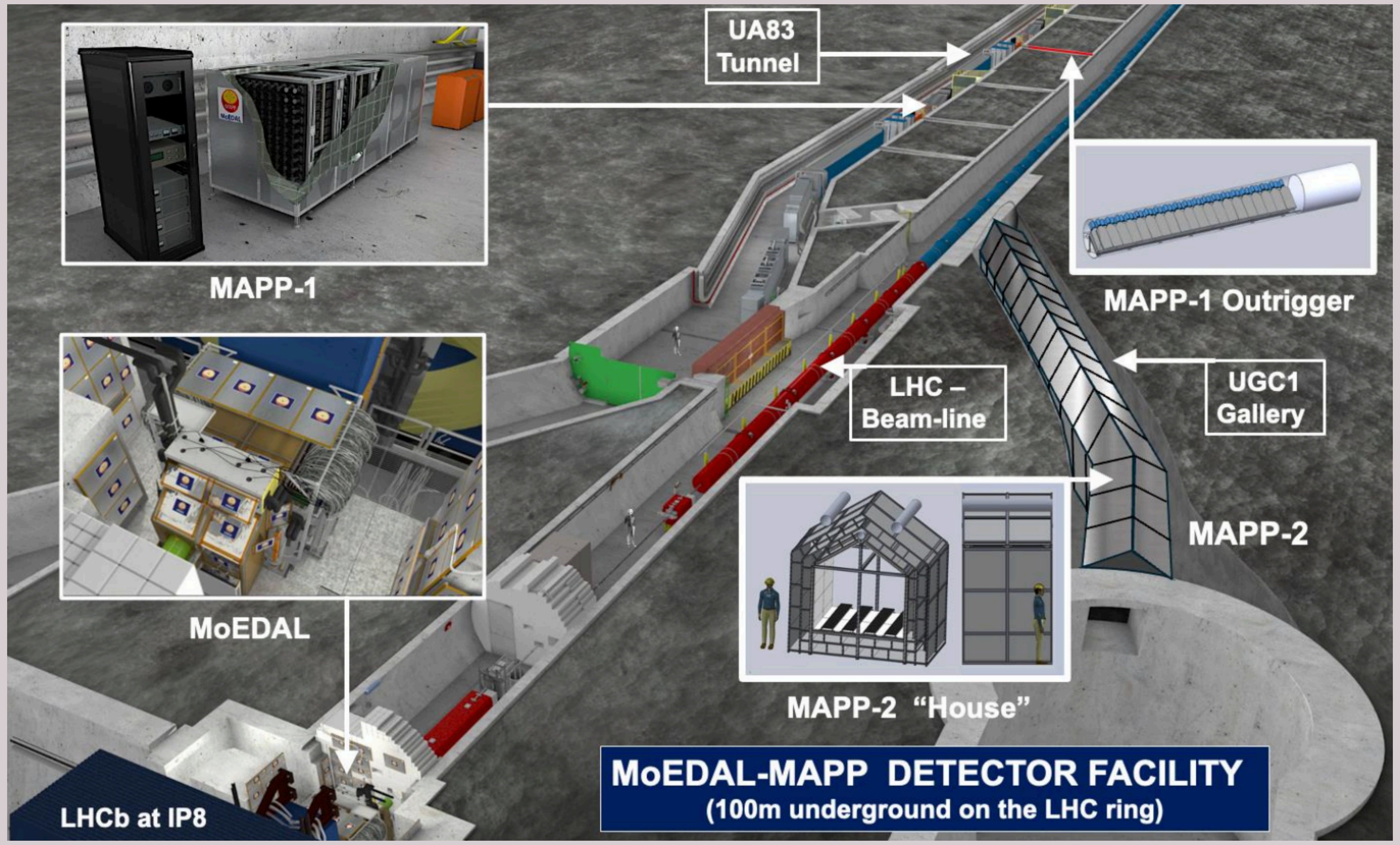
Sensitive to very forward LLPs: light dark photons, HNLs and scalars from meson decays, and ALPs. Upgrading to larger FASER2 for HL-LHC.

See: arXiv:1811.12522



MoEDAL-MAPP

Sensitive to LLP decays in the intermediate pseudorapidity range: HNLs and scalars from meson decays, millicharged LLPs (and magnetic monopoles). Upgrading to larger MAPP-2 for HL-LHC. See: PoS LHCP2023 (2024) 011

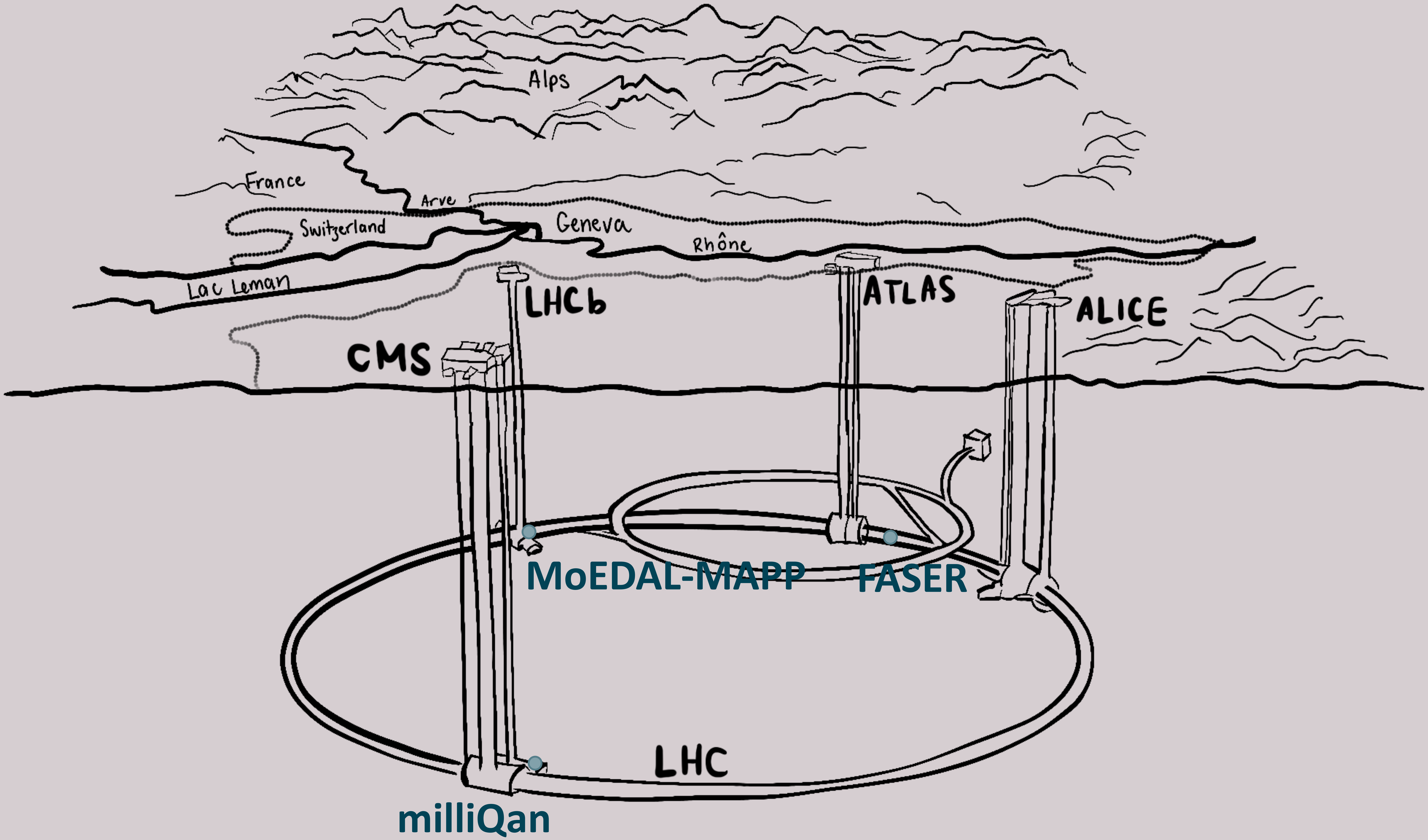


milliQan

Sensitive to millicharged LLPs, located in a tunnel above CMS

See: Phys. Rev. D 104, 032002

Existing auxiliary detectors



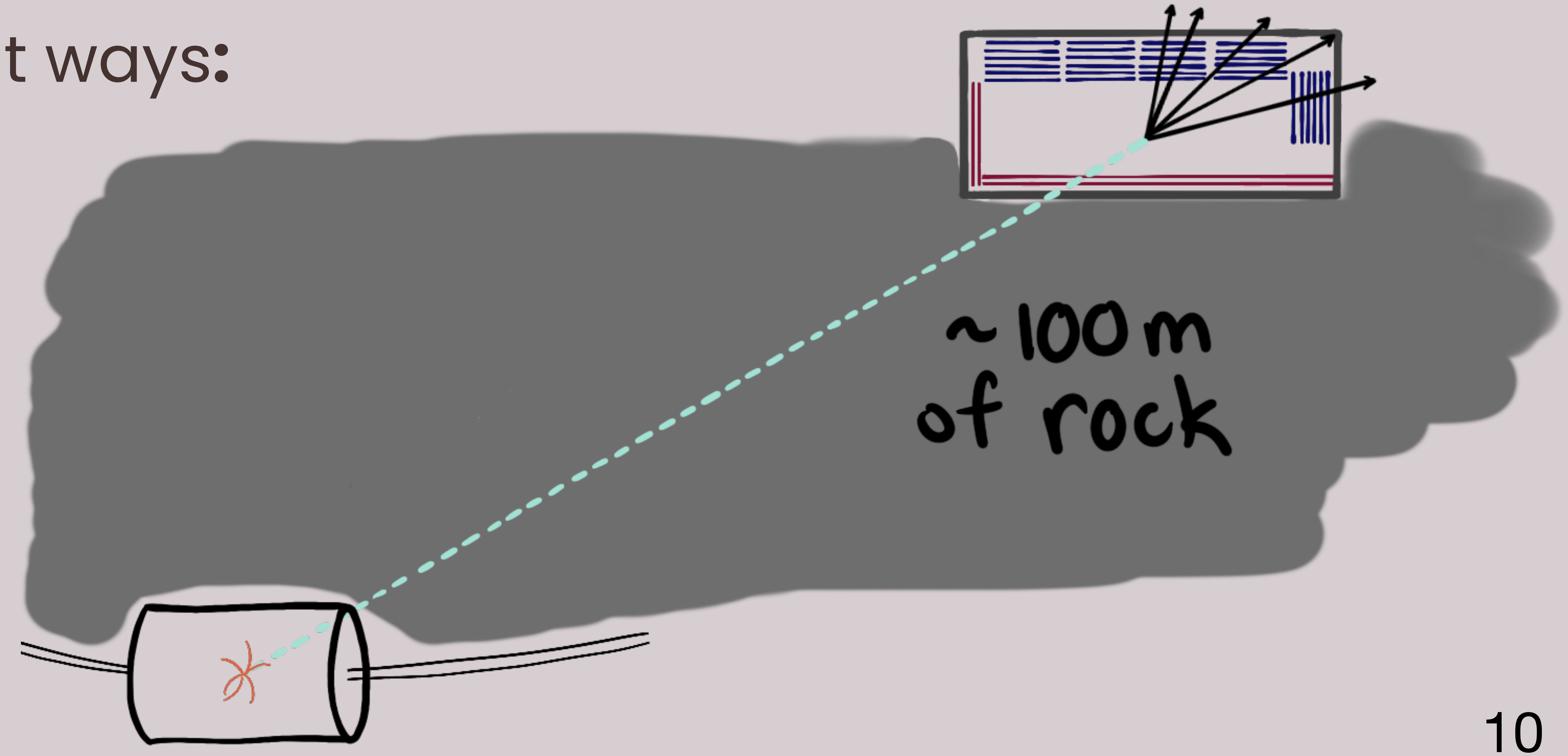
How do we do better?

Long-lived particles **do not interact** with any SM particles — either in the detector or the rock surrounding the detector

Many SM particles mimicking LLP decays evade normal detection but will eventually interact with material

We can improve in a few different ways:

1. Build a detector farther away so it has access to larger decay positions/ longer lifetimes



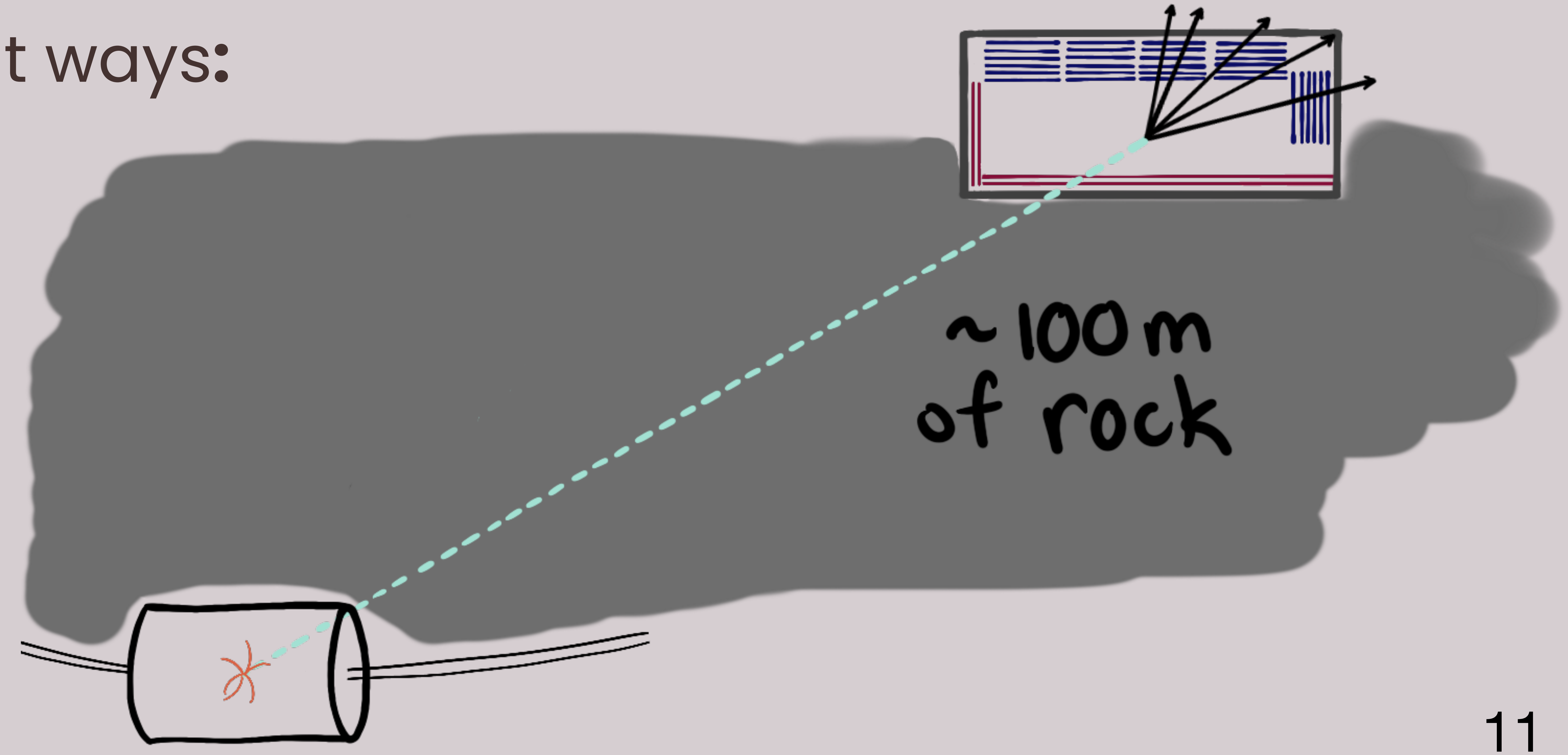
How do we do better?

Long-lived particles **do not interact** with any SM particles — either in the detector or the rock surrounding the detector

Many SM particles mimicking LLP decays evade normal detection but will eventually interact with material

We can improve in a few different ways:

2. Build the detector farther away from the LHC interaction point so the rock acts as a **shield**



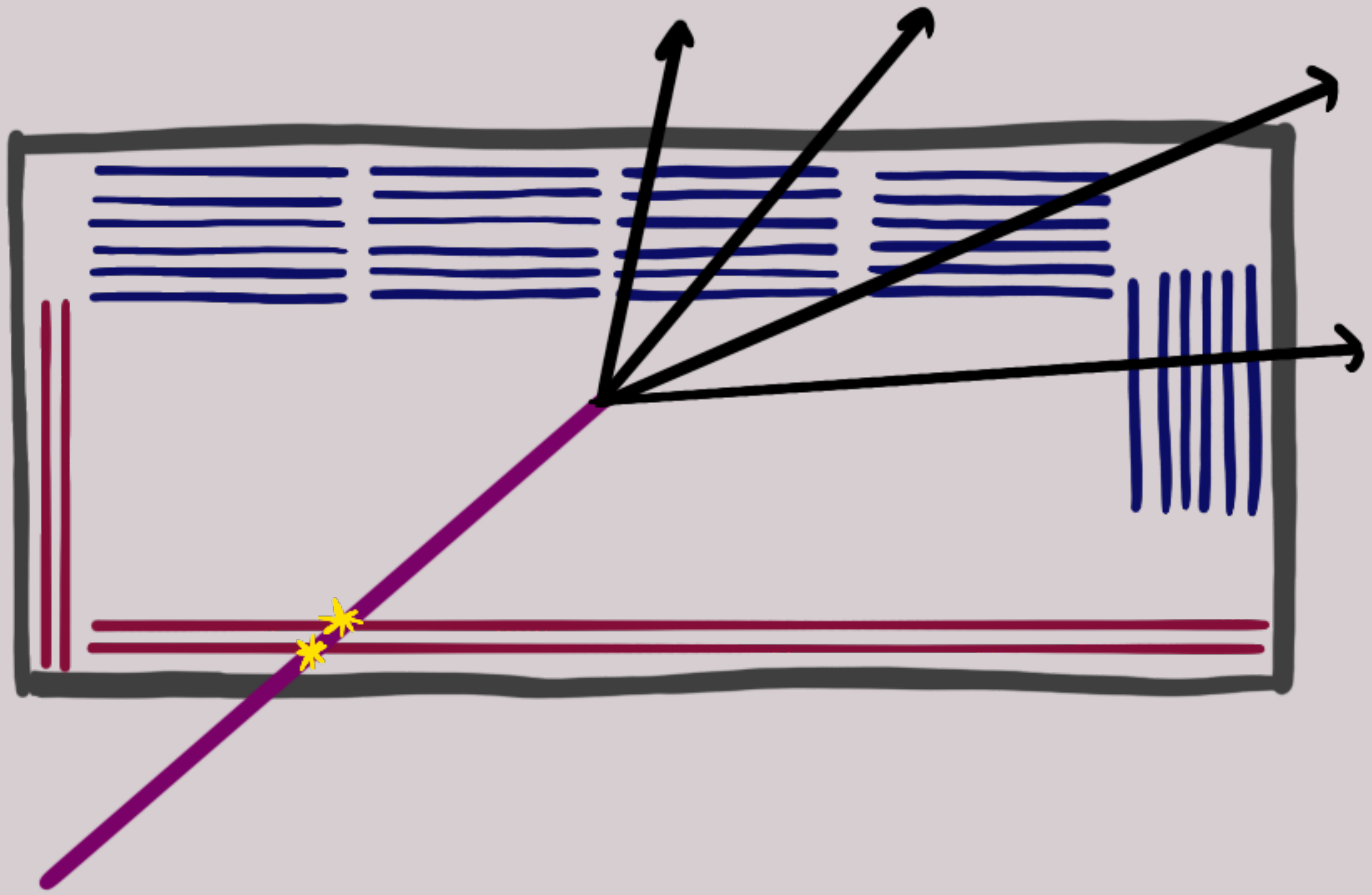
How do we do better?

Long-lived particles **do not interact** with any SM particles — either in the detector or the rock surrounding the detector

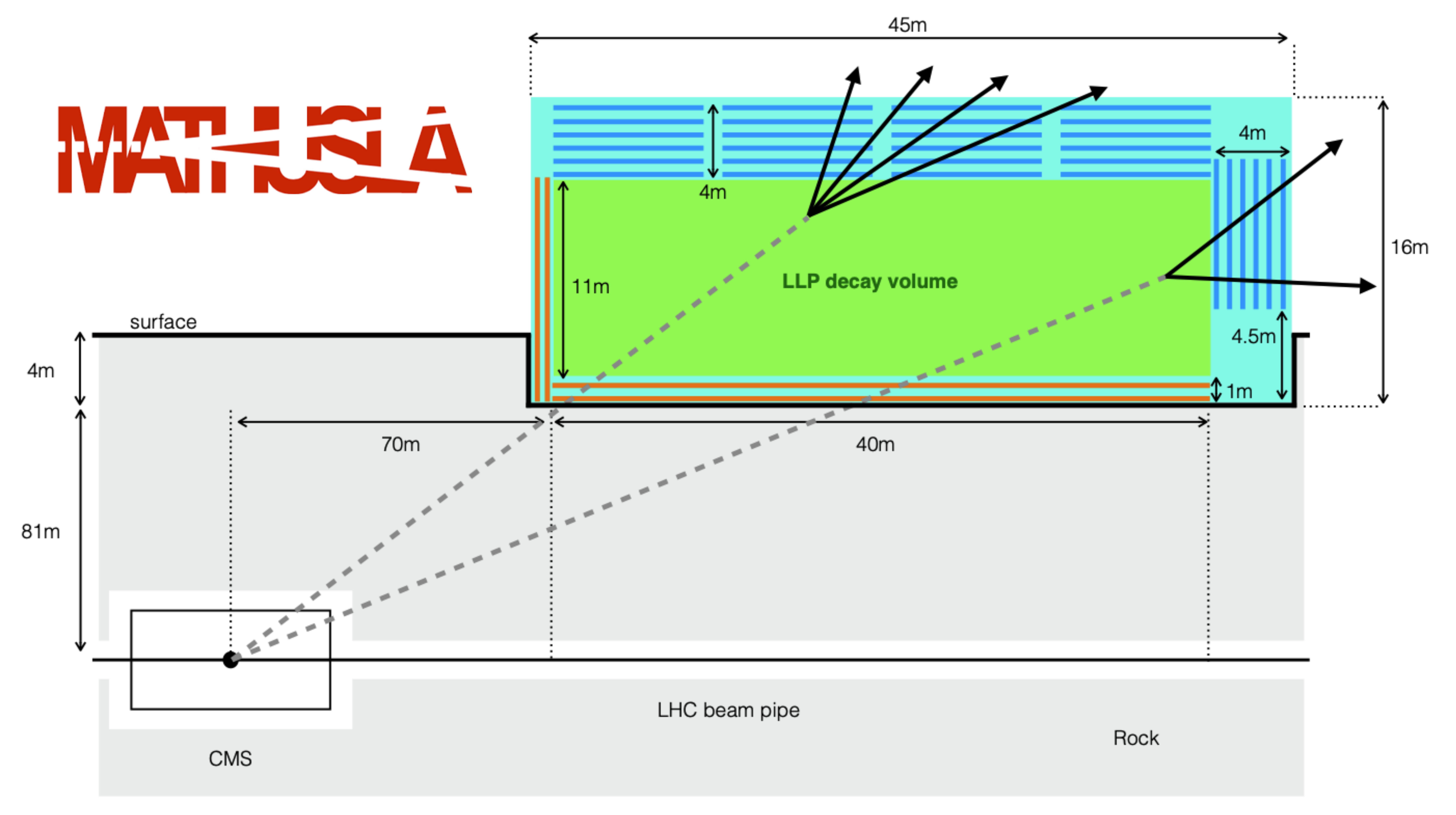
Many SM particles mimicking LLP decays evade normal detection but will eventually interact with material

We can improve in a few different ways:

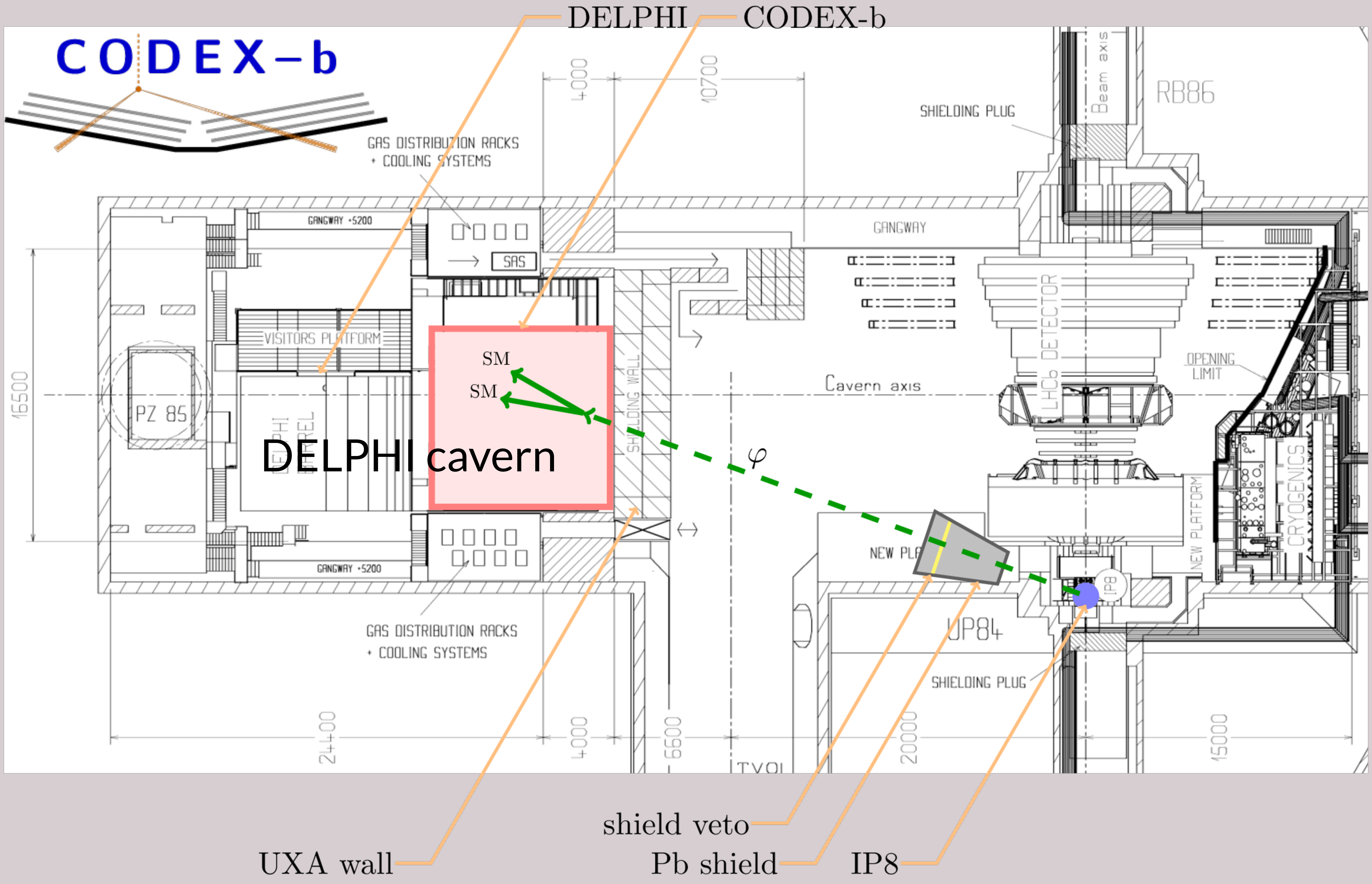
3. Incorporate a **veto layer** into the bottom of the detector to identify and remove remaining SM backgrounds



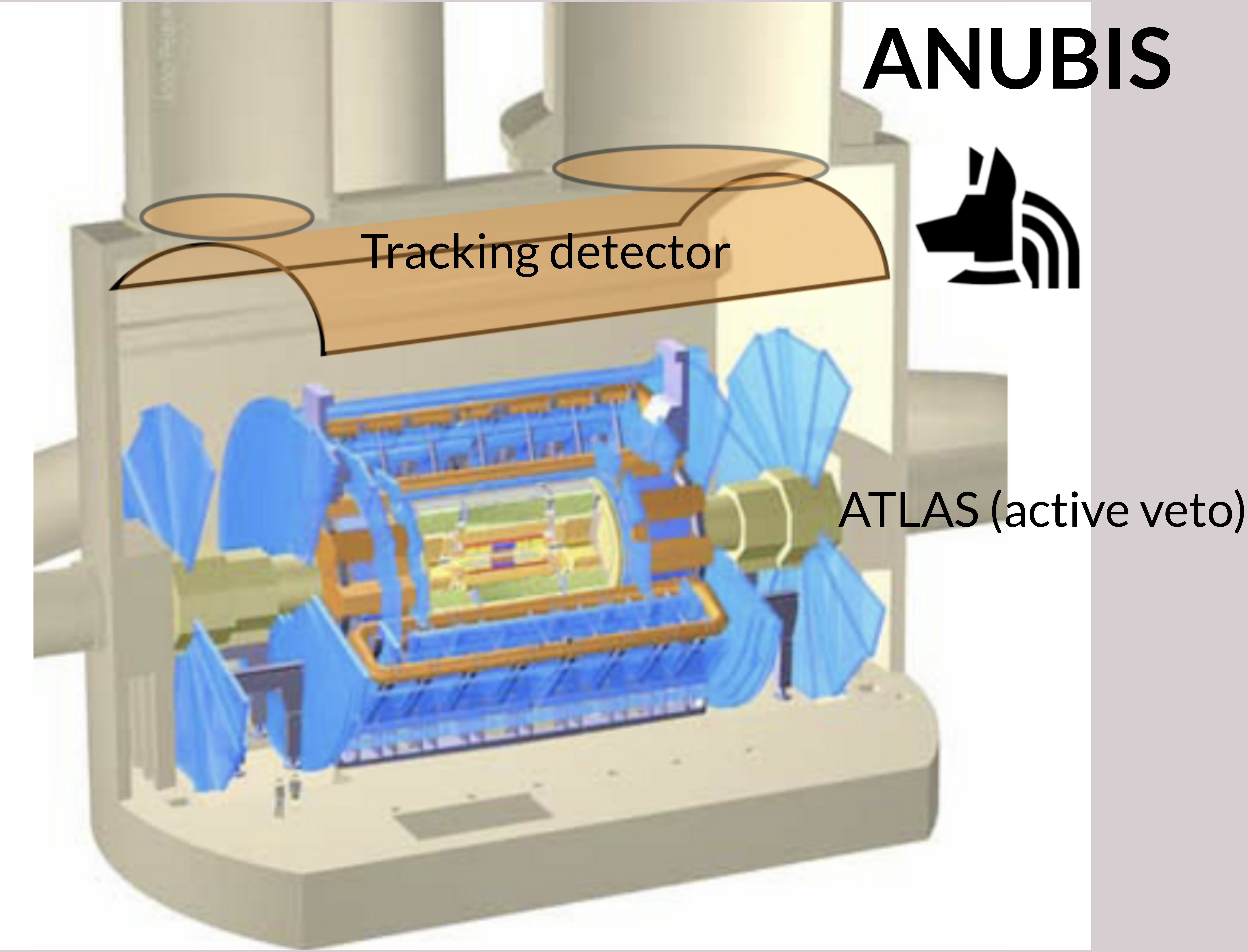
Proposed transverse detectors



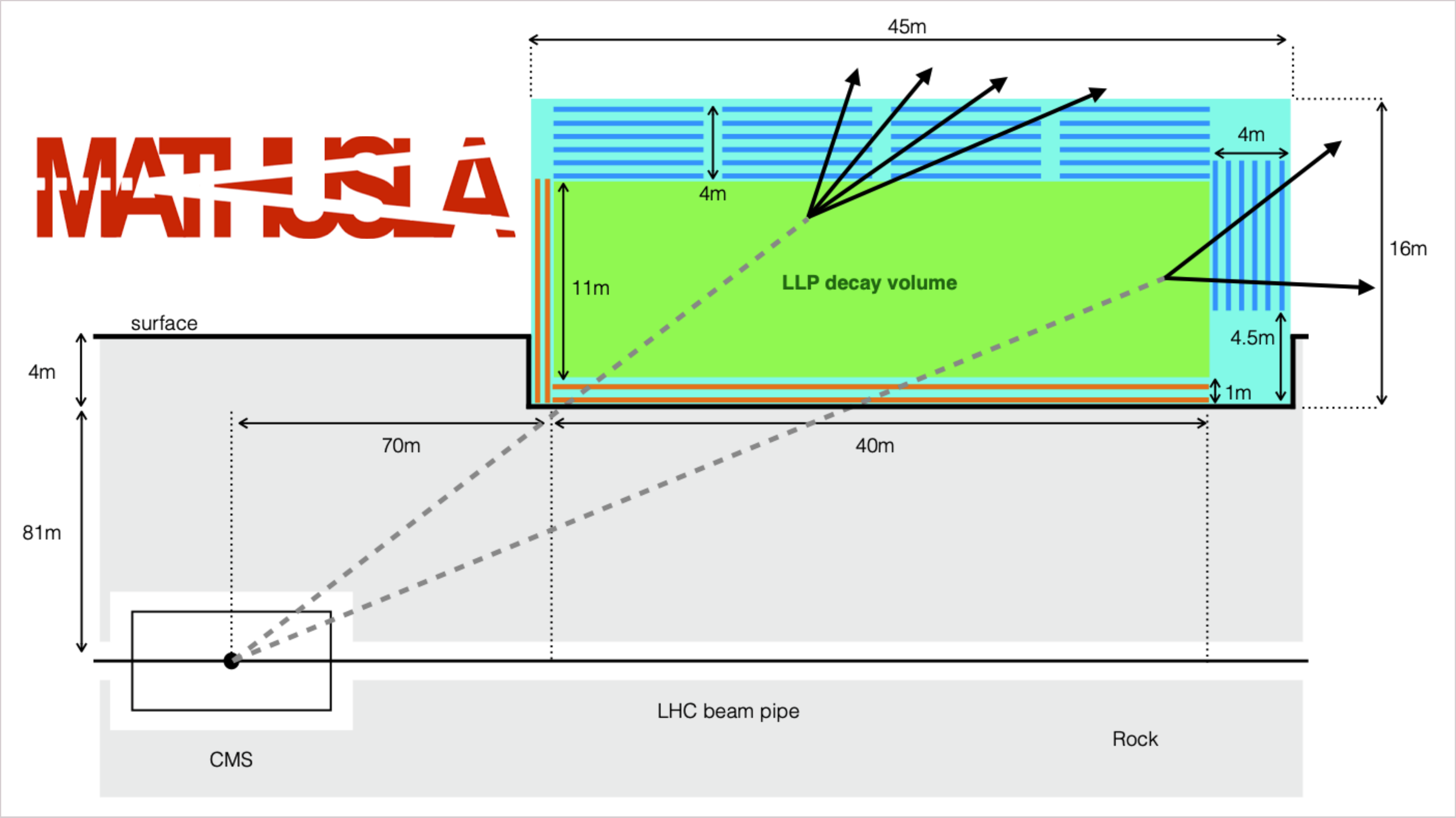
Proposed transverse detectors

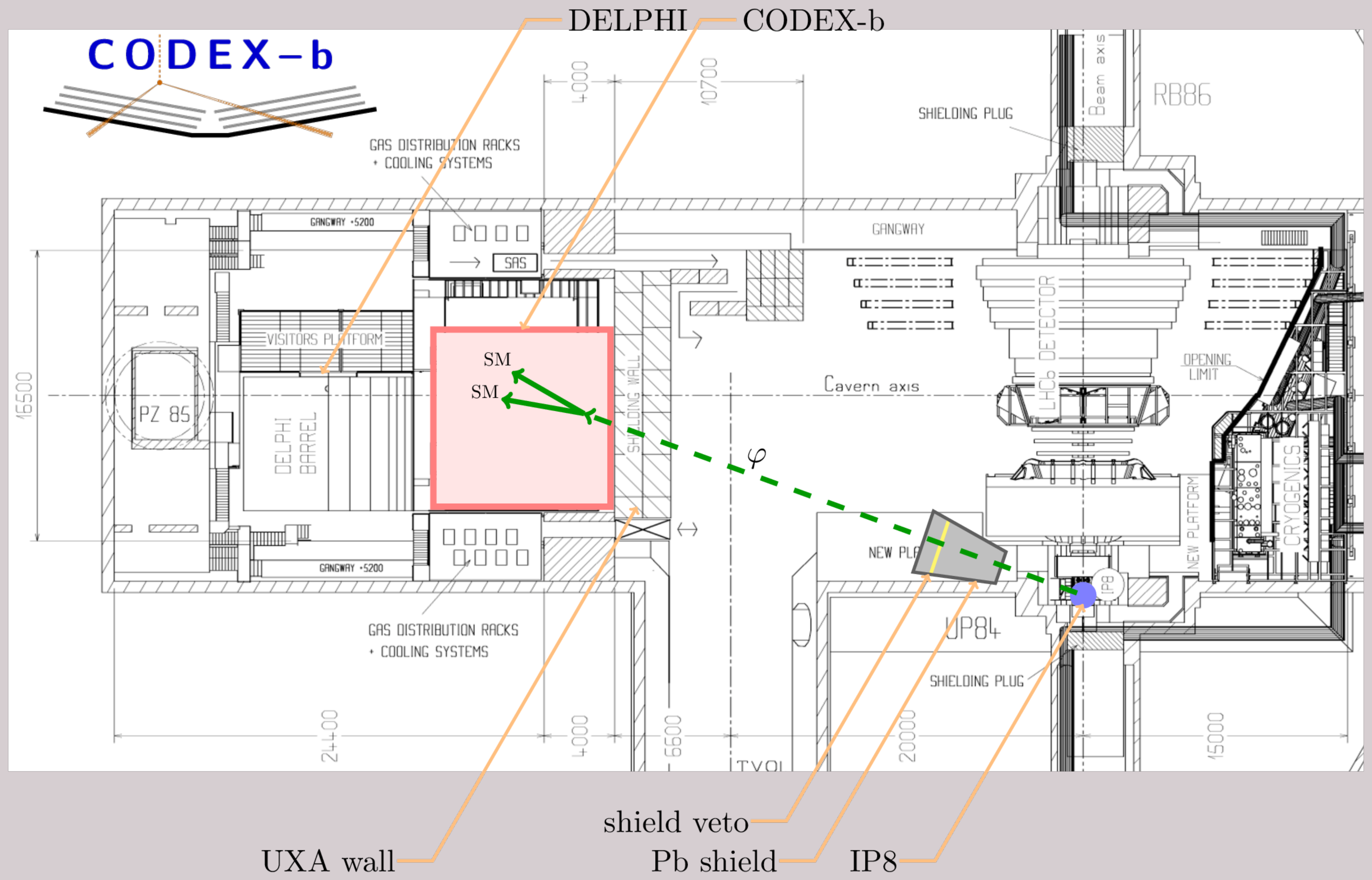


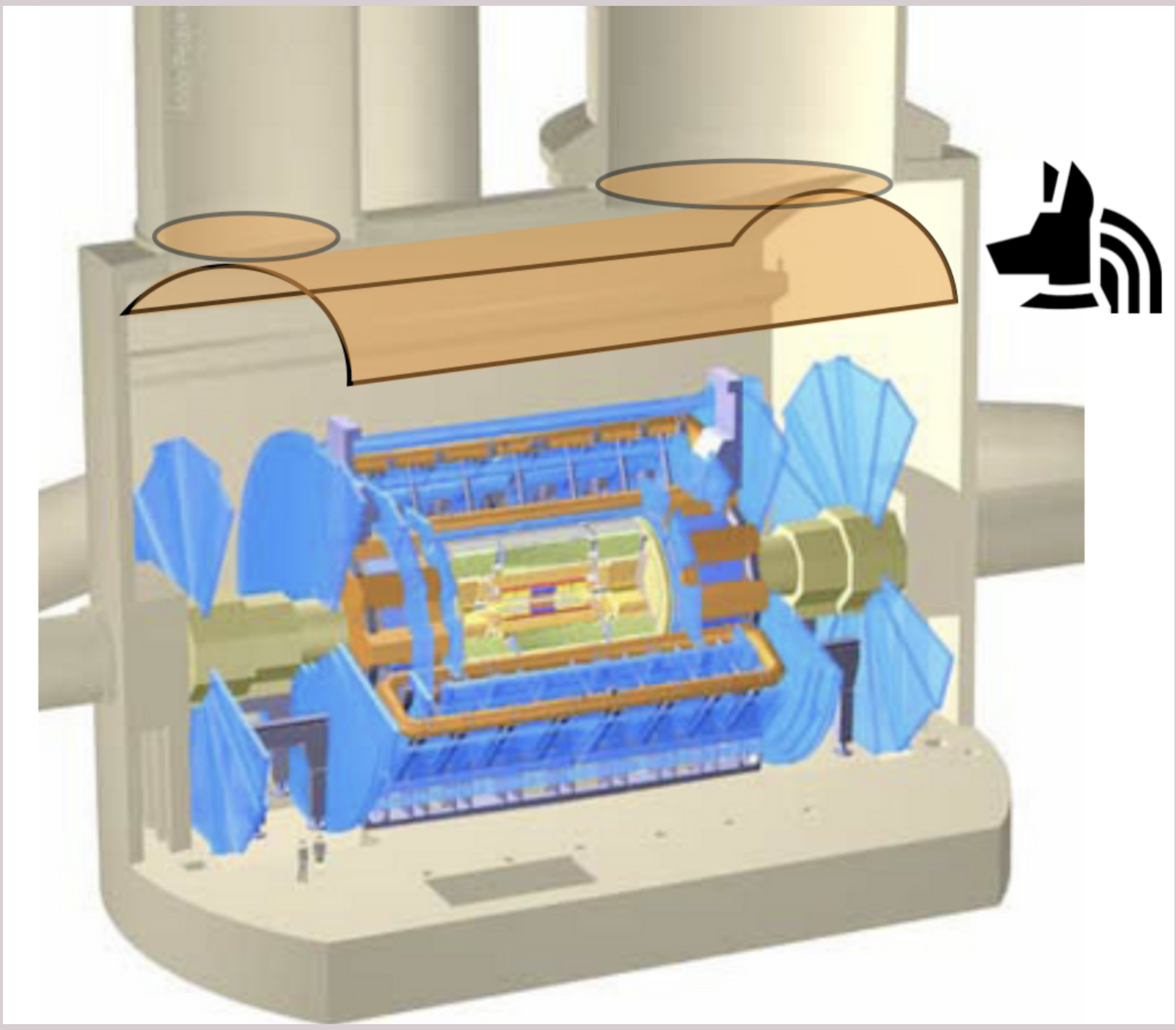
Proposed transverse detectors



Proposed transverse detectors







Farthest from an LHC IP

- Sensitive to longer lifetimes
- Smaller solid angle coverage/need a physically larger detector
- Rock absorbs SM backgrounds

Requires CERN land and infrastructure

Surface detector is easy to build/ access/maintain during beams

Reuses existing underground space

- Closer to IP, no rock - add a shield & active veto
- Smaller cosmic background
- LHCb wants the cavern for computing

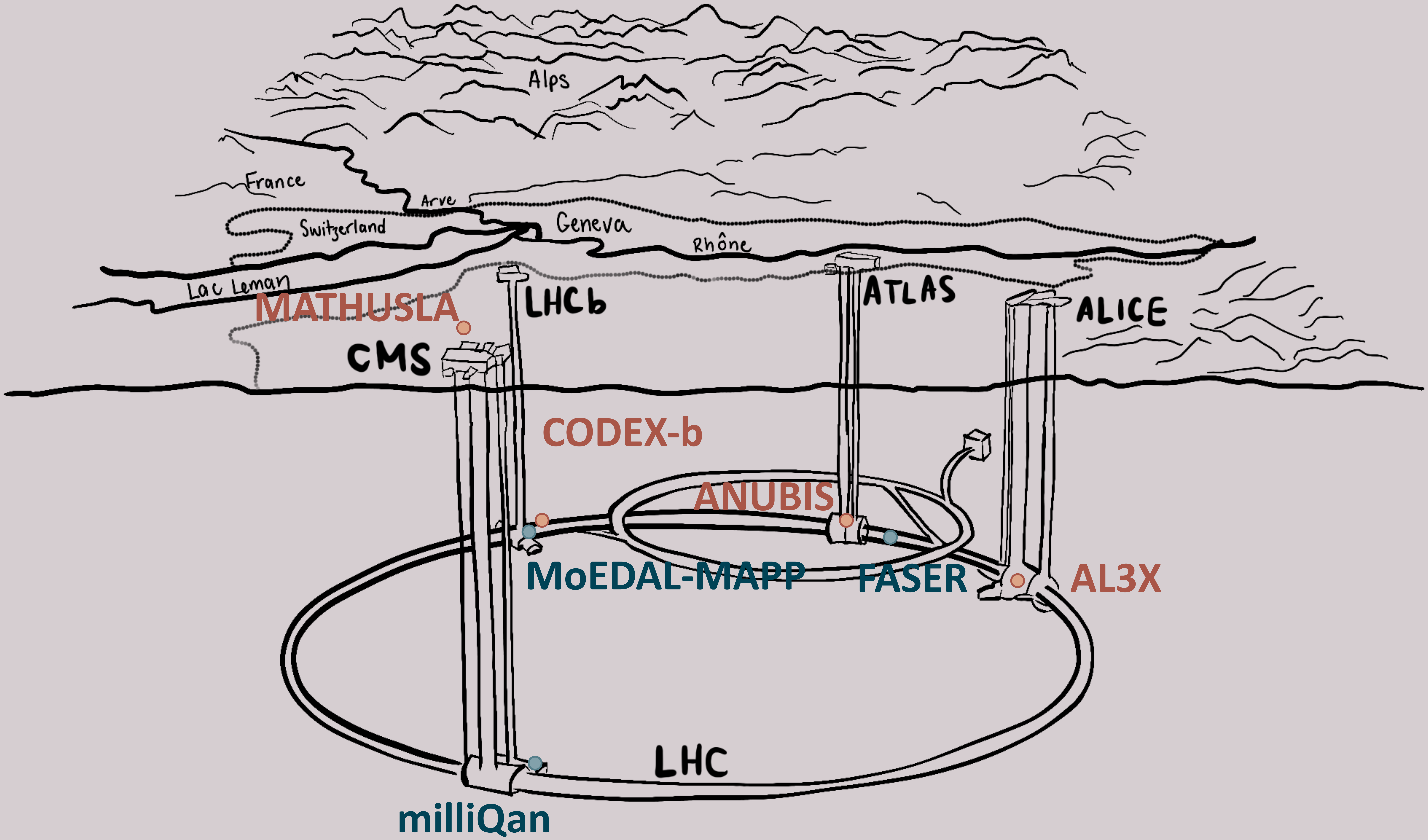
Suffer from lower luminosity: LHCb levels much lower than ATLAS/CMS

Takes advantage of empty space above ATLAS

- Can only install for Run 5

Much closer to IP: easy to link up to ATLAS but much higher background to deal with

Proposed auxiliary detectors



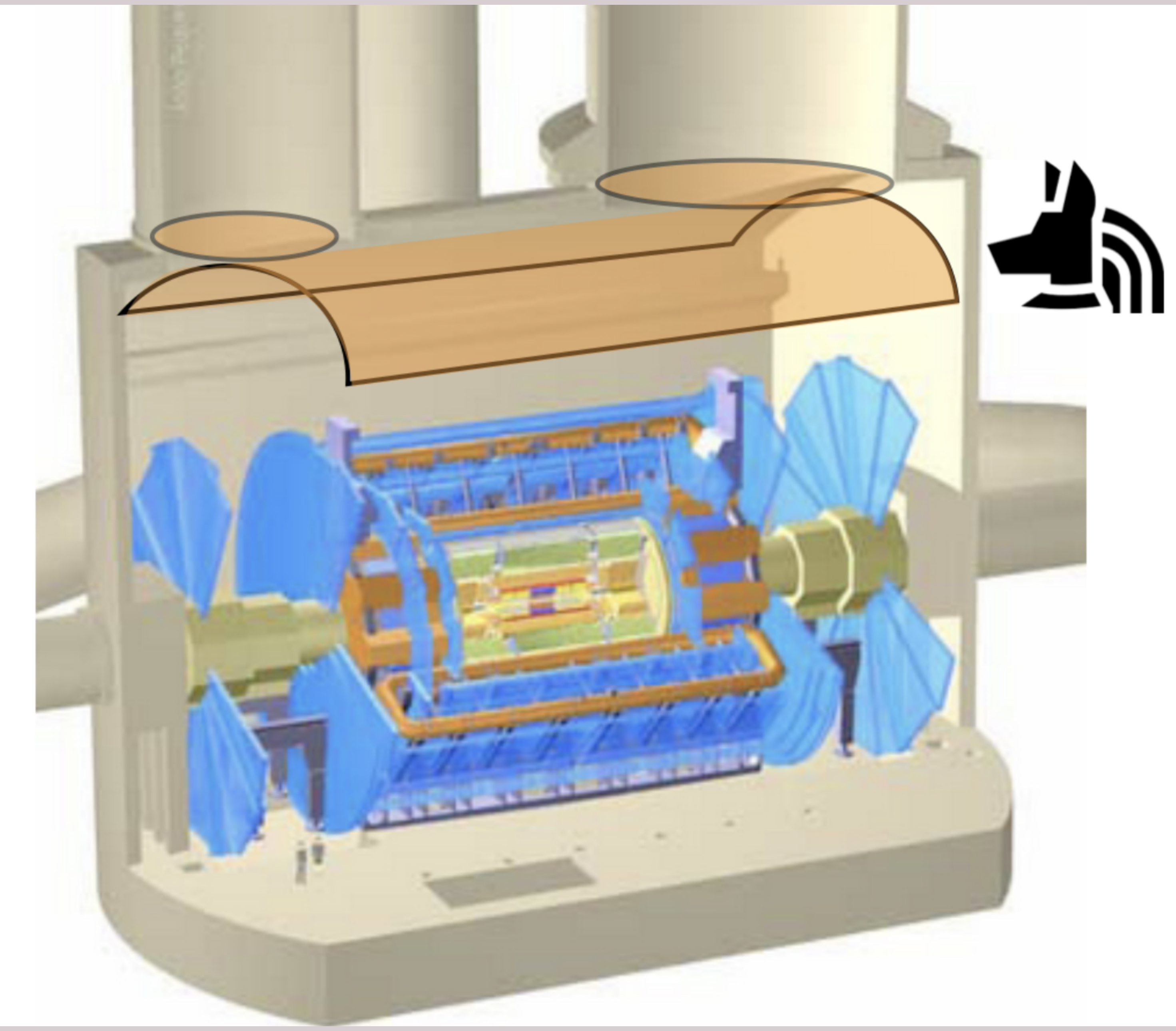
So what can we do at a future collider?

1. **Design a detector with better LLP sensitivity from the start**

These dedicated LLP proposals exist because the LHC general purpose detectors don't have sufficient sensitivity

We don't need to start from that baseline assumption.

Consider ANUBIS, which is just a few tracking layers above ATLAS. Why does this need to be its own detector?



What if we just built FCC detectors with an outer sub-detector?

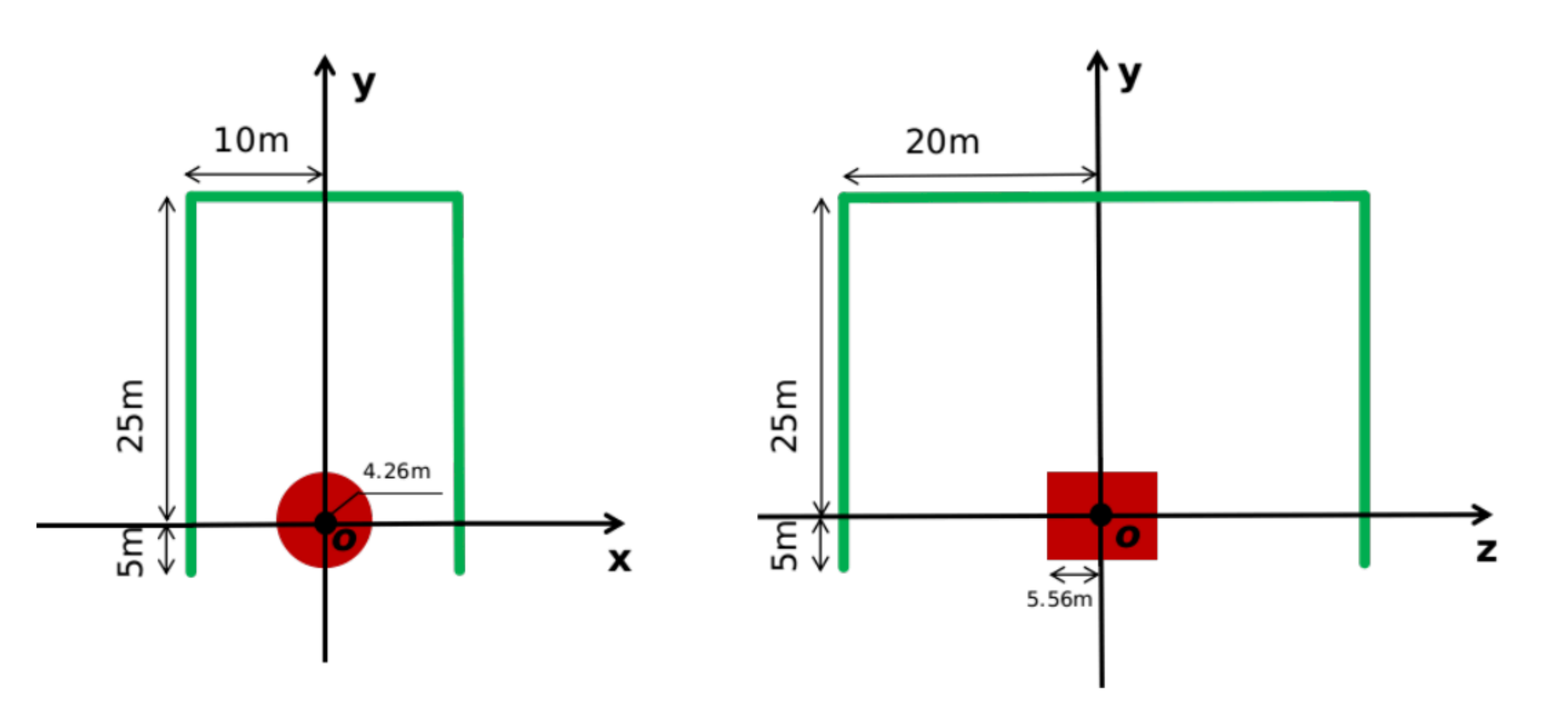
Proposed FCC detectors – I

HECATE (https://arxiv.org/abs/2011.01005)

“At a future lepton collider the detectors **will be smaller** than those of the LHC, which limits the sensitivity to long lifetimes. However, the current planning for the FCC-ee and CEPC foresees to build a hadron collider in the same tunnel, namely the FCC-hh or SPPC [14, 15] … instrumenting this extra space could considerably increase the sensitivity of the FCC-ee … to LLPs”

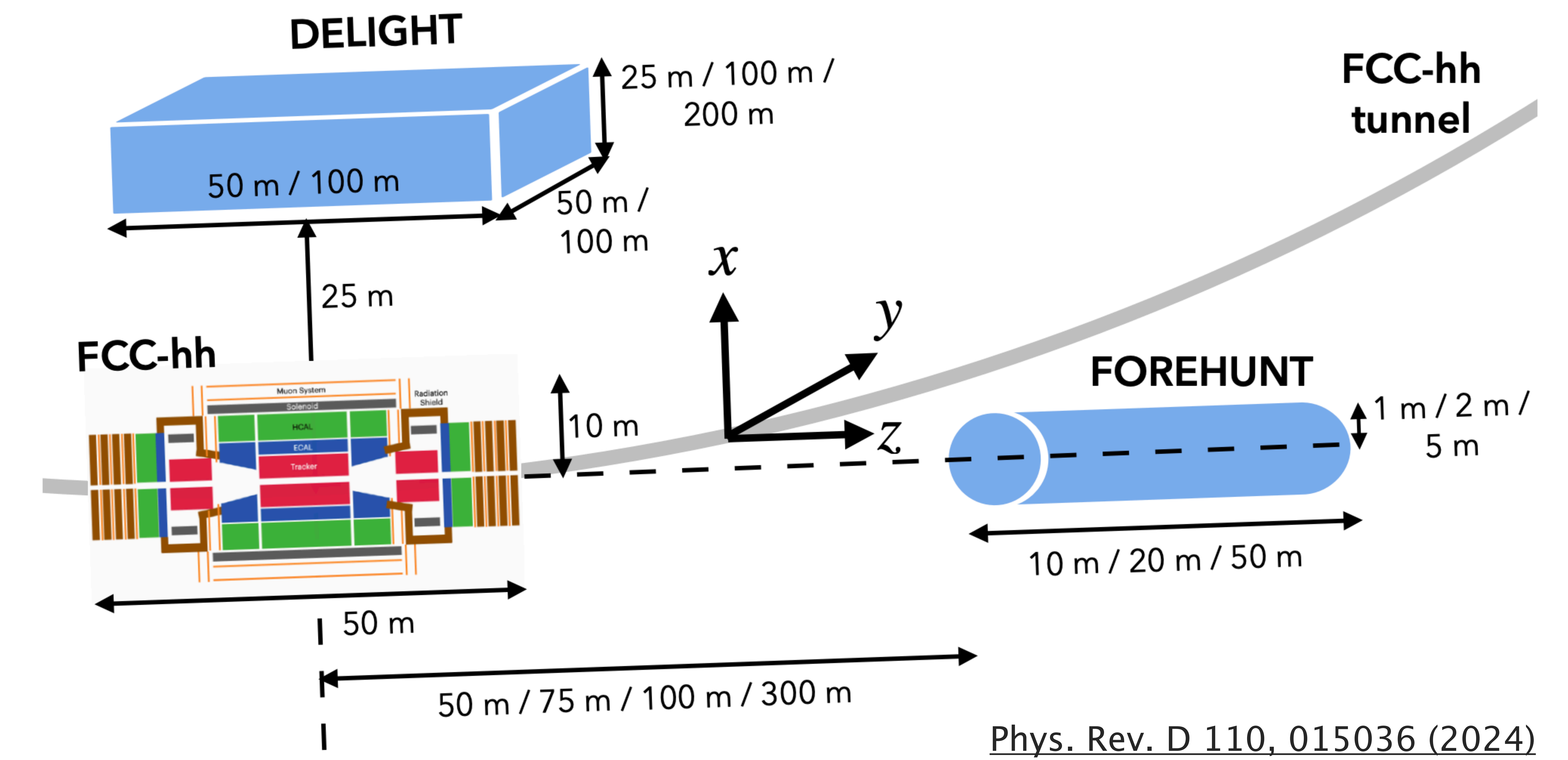
LAYCAST (https://arxiv.org/pdf/2406.05770)

Refined version of HECATE, not hermetic.
“More realistic”



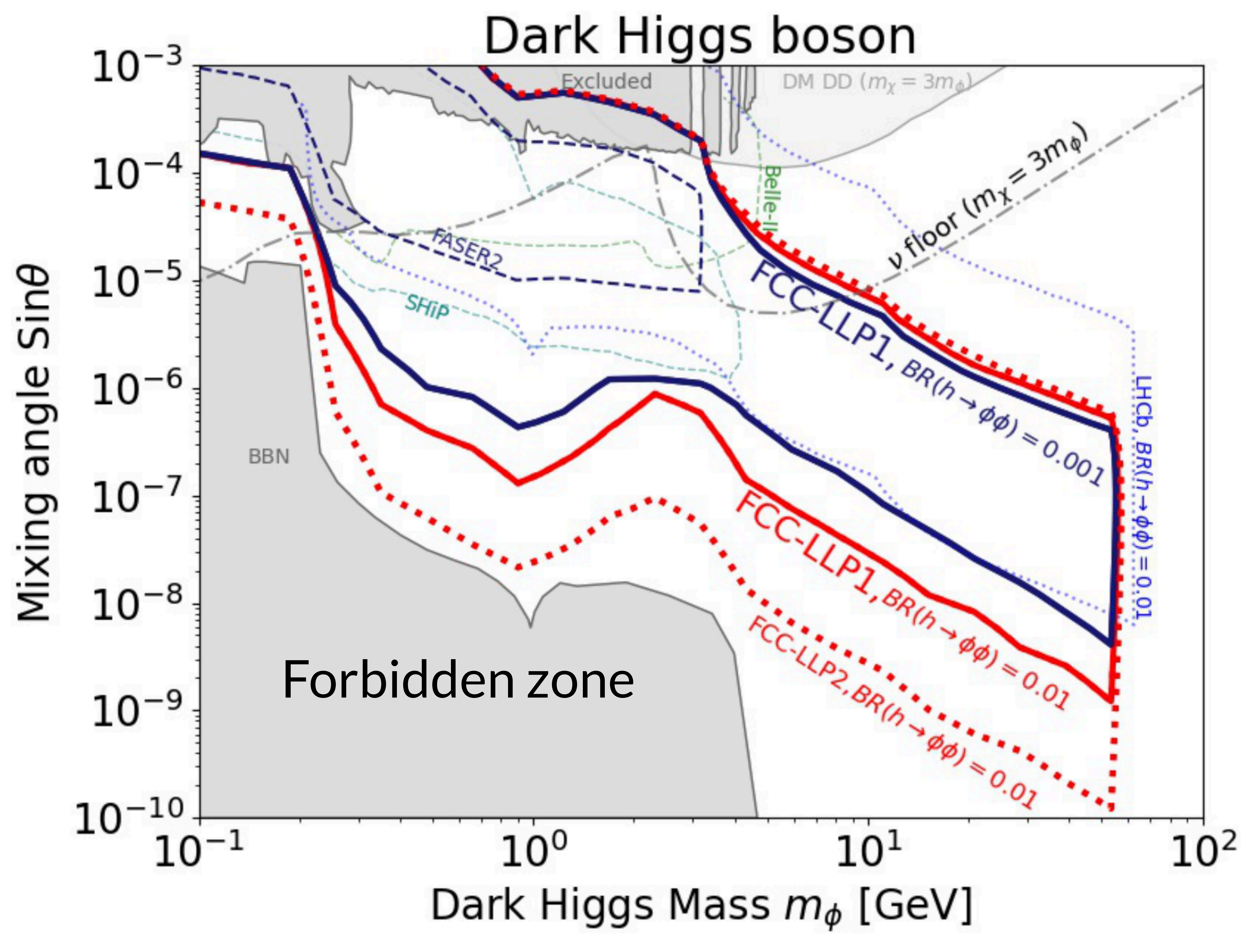
Proposed FCC detectors – II

FOREHUNT & **DELIGHT**: “MATHUSLA + FASER” approach to LLP detection



Phys. Rev. D 110, 015036 (2024)

Proposed FCC detectors – III



FASER-like strategy

At (HL-)LHC, Higgs decays are central → forward sensitivity is from $B \to K\phi$

At FCC-hh, Higgs bosons are **boosted** and forward experiments gain sensitivity to LLPs from Higgs decays

https://arxiv.org/pdf/2105.07077

FCC-LLP1	5 m × 5 m × 50 m	30 ab^{-1}	100 TeV	$E_{\text{vis}} \gtrsim 100$ GeV
FCC-LLP2	20 m × 20 m × 400 m	30 ab^{-1}	100 TeV	$E_{\text{vis}} \gtrsim 100$ GeV

Things we would need to think about now

(1) Do we want to advocate for modifications to the proposed detectors?

- Current detector plans do not incorporate enhanced sensitivity to LLPs

(2) Are there any underground locations we could consider repurposing?

- Like Codex-b in the Delphi cavern

(3) Are there any detectors/magnets that we could consider repurposing?

- Like the AL3X 'proposal' to create a dedicated LLP detector from ALICE

(4) If we decide we need a surface detector, what land can it go on?

- CERN land isn't necessarily "available" and land usage/road access is planned decades in advance (see: CERN Master Plan 2040)

Summary

The proposed LLP detectors for HL-LHC came about because the central detectors have limited sensitivity

We have a chance to improve this for FCC, but this would need to start soon

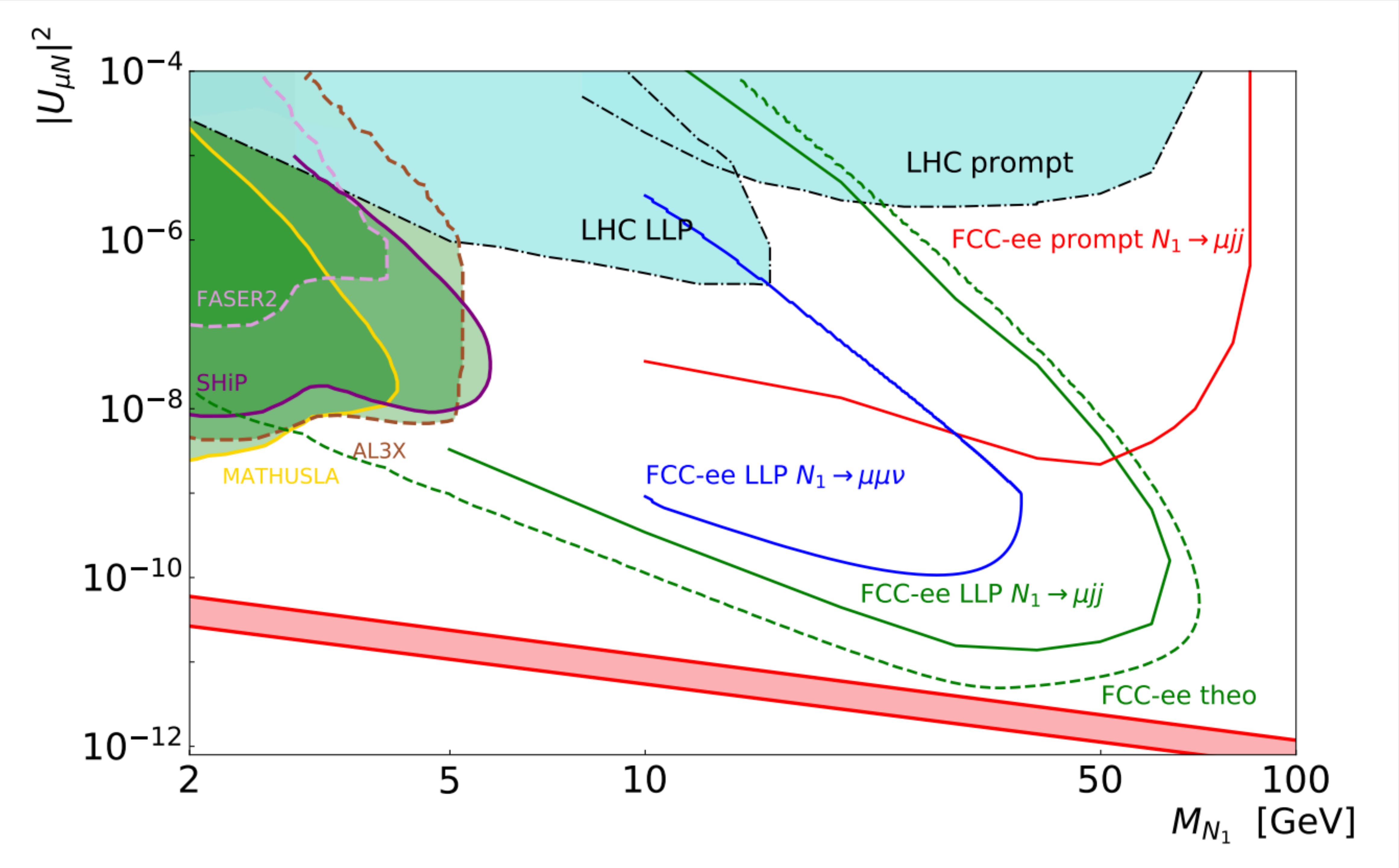
Large area **muon detectors** are needed to instrument the outer layers, with a resolution of a few hundred micrometers [901] . To detect long-lived particles (LLPs) and other exotic particles, which are candidates for dark matter, self-triggering and stand-alone tracking capabilities are required, resulting in granular cells and multiple layers. Gas-based systems will require eco-friendly gas mixtures [881].

FCC-ee general purpose detectors

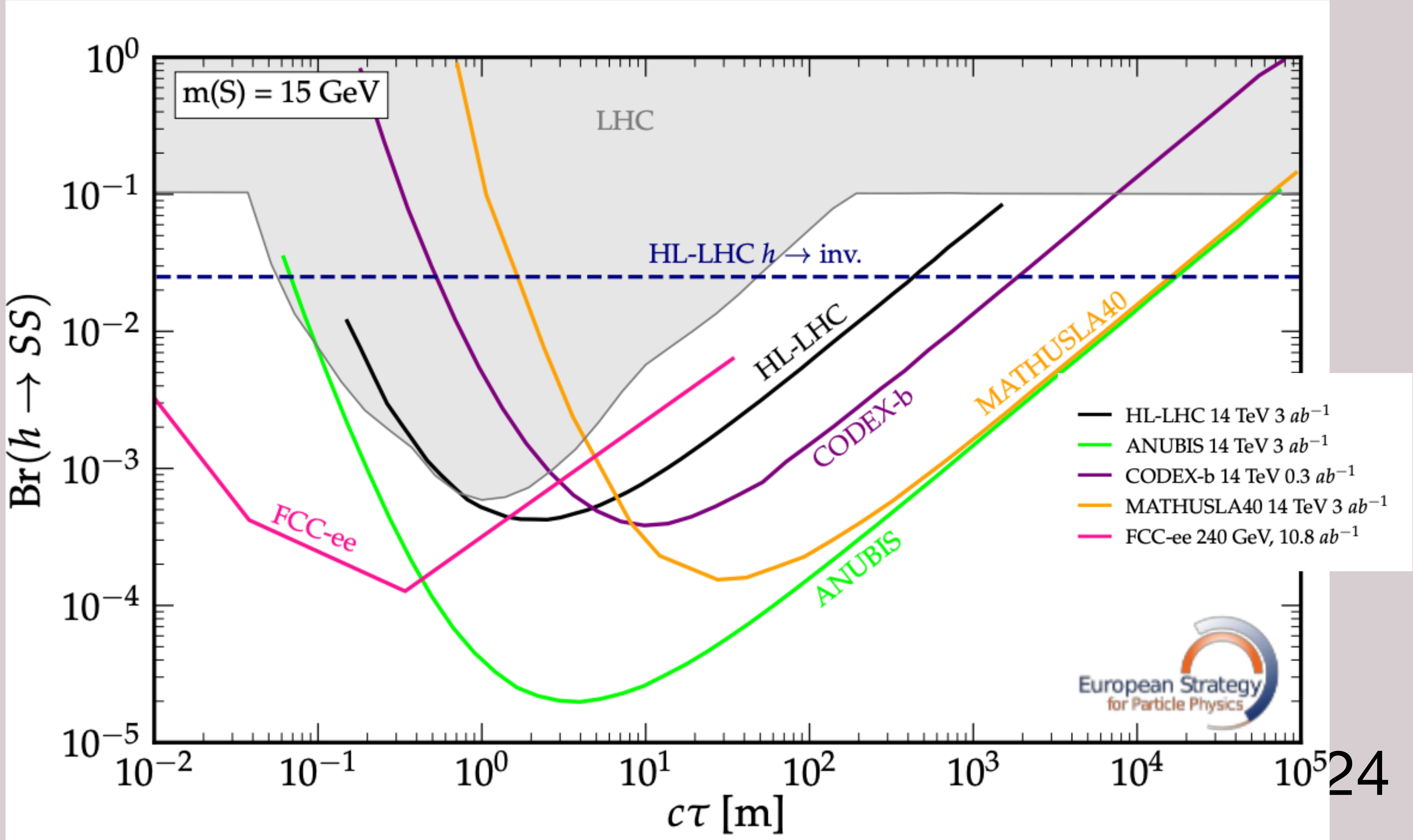
Higgs → invisible branching fraction FCC_PED_ESPPU_BSM

particles, such as dark matter candidates or additional scalars [58]. A preliminary study shows that when accounting for the possibility of exotic decays, branching fractions lower than 0.07% can be excluded at the 95% CL or a 5σ observation can be obtained if greater than 0.18% [92, 93]. The study of jet+missing E_T at FCC-hh provides sensitivity to BR(H→invisible) at the level of few $\times 10^{-4}$ [94].

Heavy Neutral Leptons



Higgs decays ($h \to \phi\phi$)



FCC-hh specialised detectors

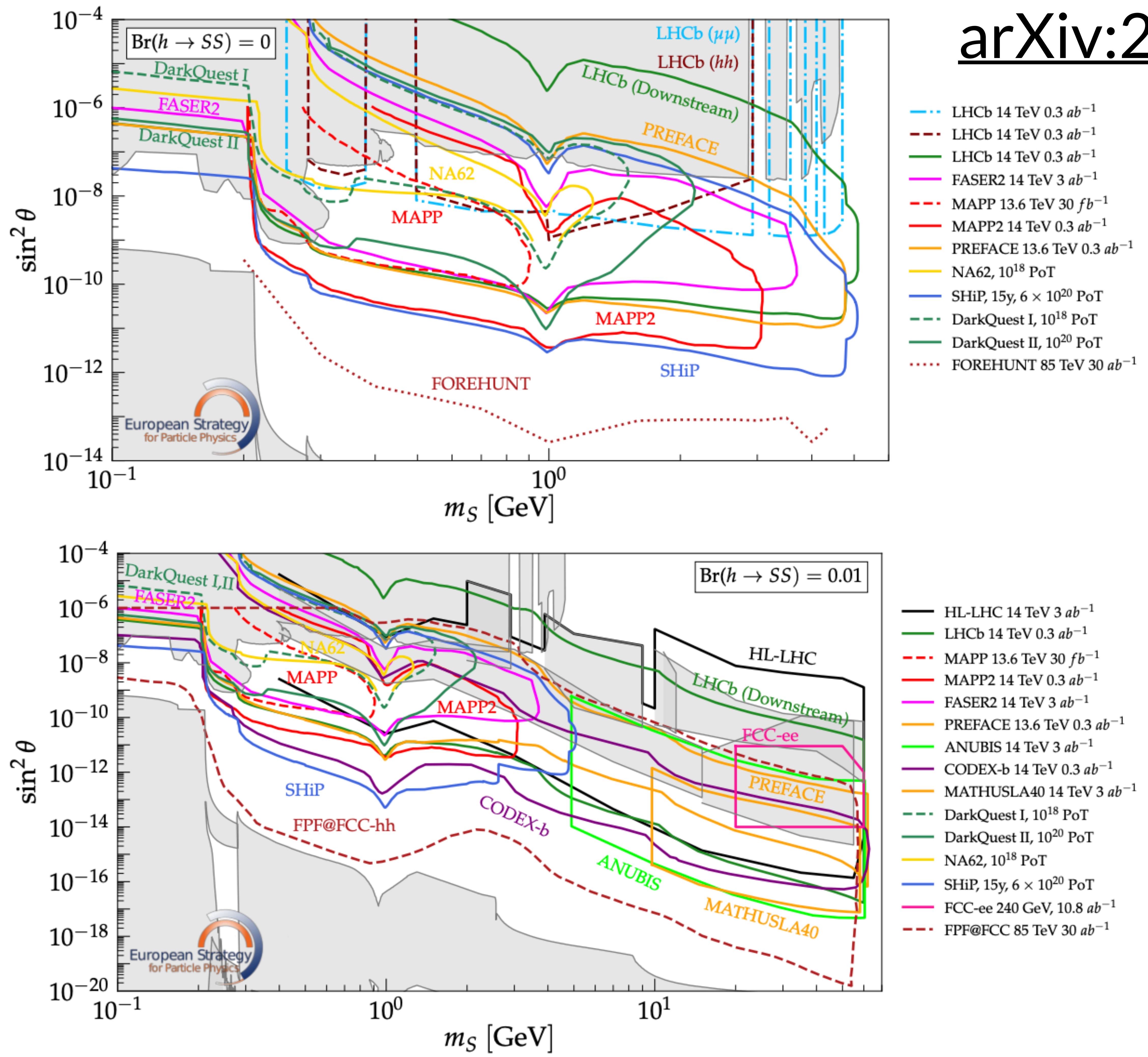


Fig. 8.17: Exclusion limits for a dark scalar mixing with the Higgs boson $\sin^2\theta$ as a function of its mass m_S, assuming that (Top) the Higgs boson does not decay to a pair of dark scalars, and (Bottom) the Higgs boson decays to a pair of dark scalars with a 1% branching fraction. Filled areas denote excluded regions, while curves show the projected sensitivities.

arXiv:2511.03883

Note the LHCb “Downstream” limit

Having forward tracking gains you a huge amount!

Details on LHCb limit: LHCb Upgrade II Discovery Potential

Other LHC detector proposals

FACET -> PREFACE (FASER-like detector by CMS): https://arxiv.org/abs/2502.14598

AL3X (repurpose ALICE detector if they won't run past HL-LHC Run 4): https://arxiv.org/abs/1810.03636

Forward Physics Facility for HL-LHC (would host FASER2, FORMOSA for millicharged particles): https://arxiv.org/pdf/2203.05090

Non-LHC detectors of relevance

Belle II - sensitivity to dark photons, e.g. https://arxiv.org/abs/2312.12522v1, LLPs in *B*-decays

SHiP/NA67 - approved SPS beam dump experiment, 400 GeV proton beam (charm meson decays - sensitive to light scalar LLPs, HNLs, dark photons, ALPS). Details: https://ship.web.cern.ch/

NA62 - Kaon beam, goal of measuring the rare decay K —> pi$\nu\nu$ but also sensitive to K —> pi phi & similar BSM physics, https://na62.web.cern.ch/

NA64 - beam dump searches for dark photons, https://na64.web.cern.ch/

+ many more

Some additional overview references

Physics beyond colliders BSM working group report: https://arxiv.org/pdf/1901.09966

Feebly-interacting particles workshop reports:

- 2020: https://arxiv.org/abs/2102.12143
- 2022: https://arxiv.org/abs/2305.01715
- 2025: https://arxiv.org/abs/2510.05257 (FIPs @ LHCb)

Searching for long-lived particles at the large hadron collider: https://arxiv.org/abs/1903.04497

Annual-ish Long-lived particle workshop presentations, e.g.
https://indico.cern.ch/event/1441321/, https://indico.cern.ch/e/LLP_2026