# Searches for long-lived particles at the LHC and beyond colliders


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Universitat de València

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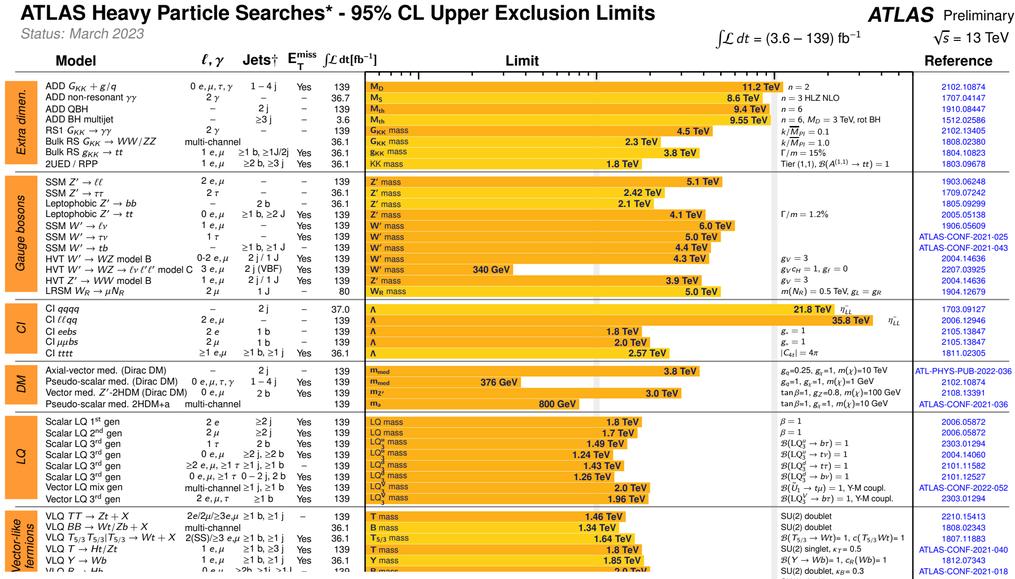
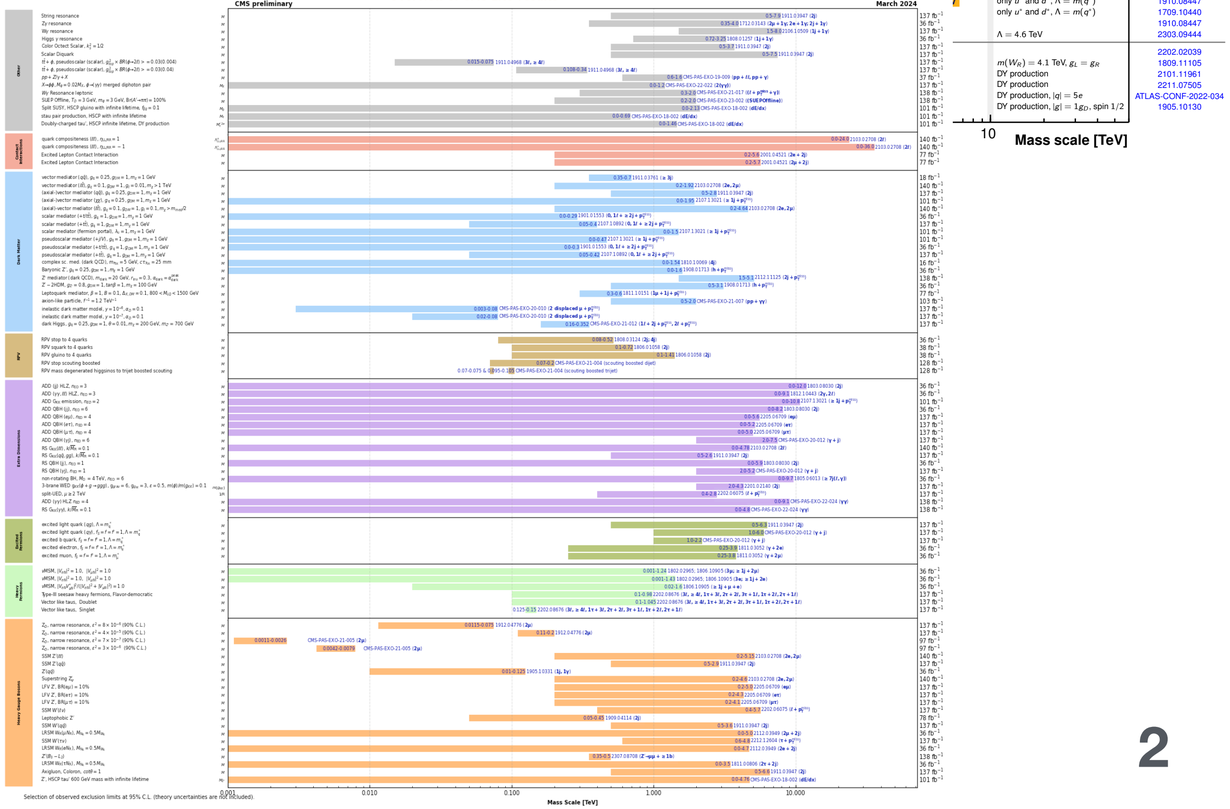
Gen-T

# Why Long-Lived Particles?

- Many ways to search for new Physics
- Effort so far has been huge… with no clue yet
- If new physics is being produced at the LHC we still need to develop the tools to see it
  - After exploring the obvious, now exploring the more complex
  - Soft objects, compressed scenarios, search in tails of distributions, heavy resonances, …. LLPs!



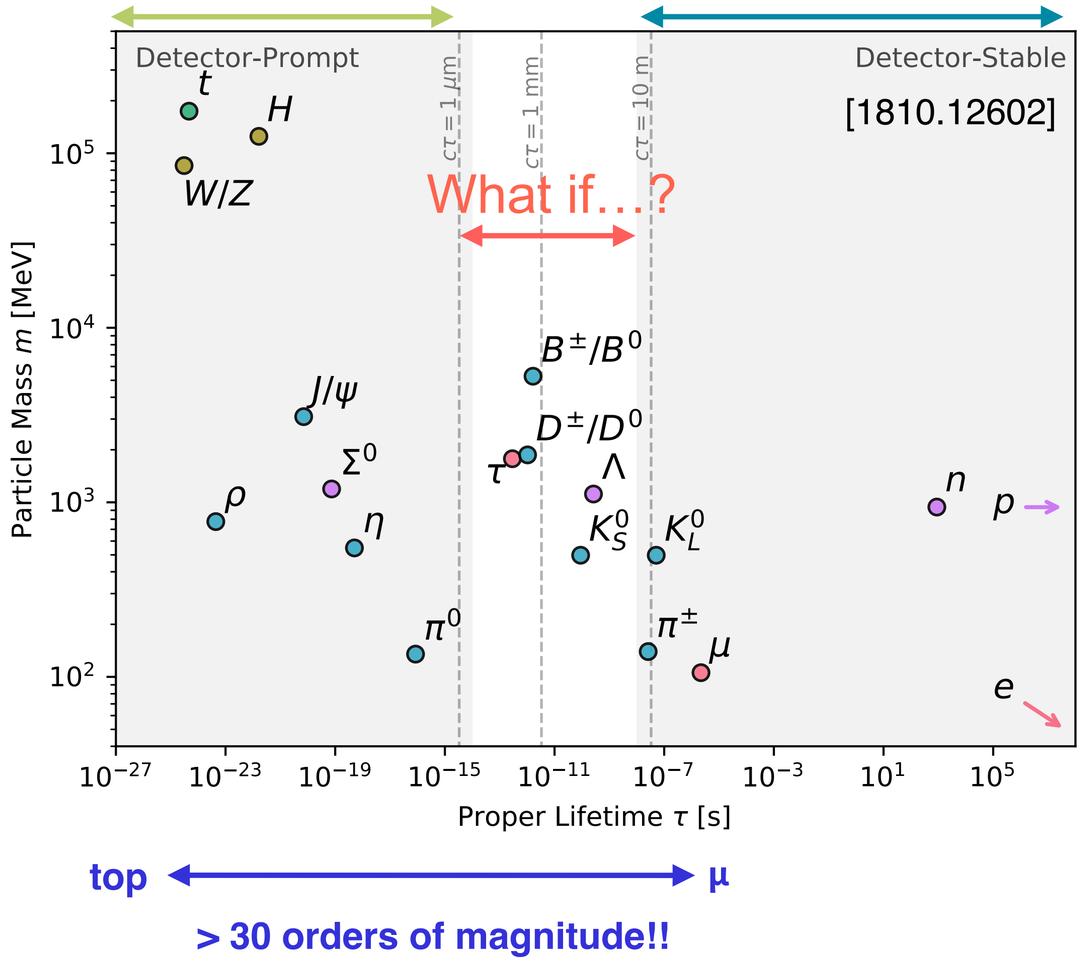



# Long Lifetimes everywhere

- Long-Lived Particles (LLPs): decay at a macroscopic distance from the Interaction Point
  - **Most BSM models** include:
    - Small couplings
    - Decays via massive particles
    - Limited phase spaces
  - **Giving rise to long lifetimes**
    - Semi-stable particles are **abundant in the Standard Model**
- It would not be surprising if they are also present in BSM physics

Prompt BSM being actively probed

Very long-lived BSM probed as MET (if produced with SM activity)

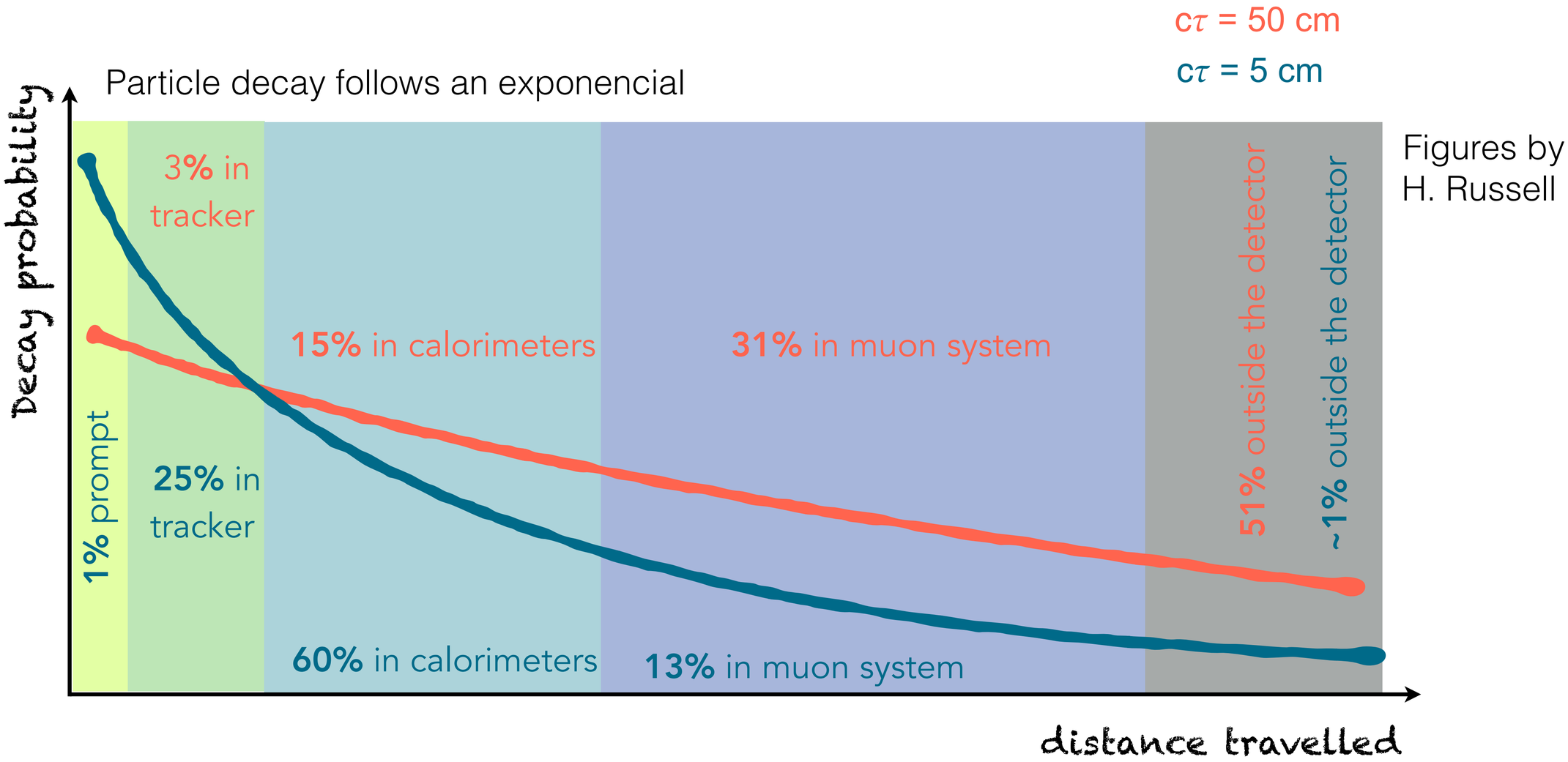



**top** ⟷ **μ**

**> 30 orders of magnitude!!**

# LLPs in colliders

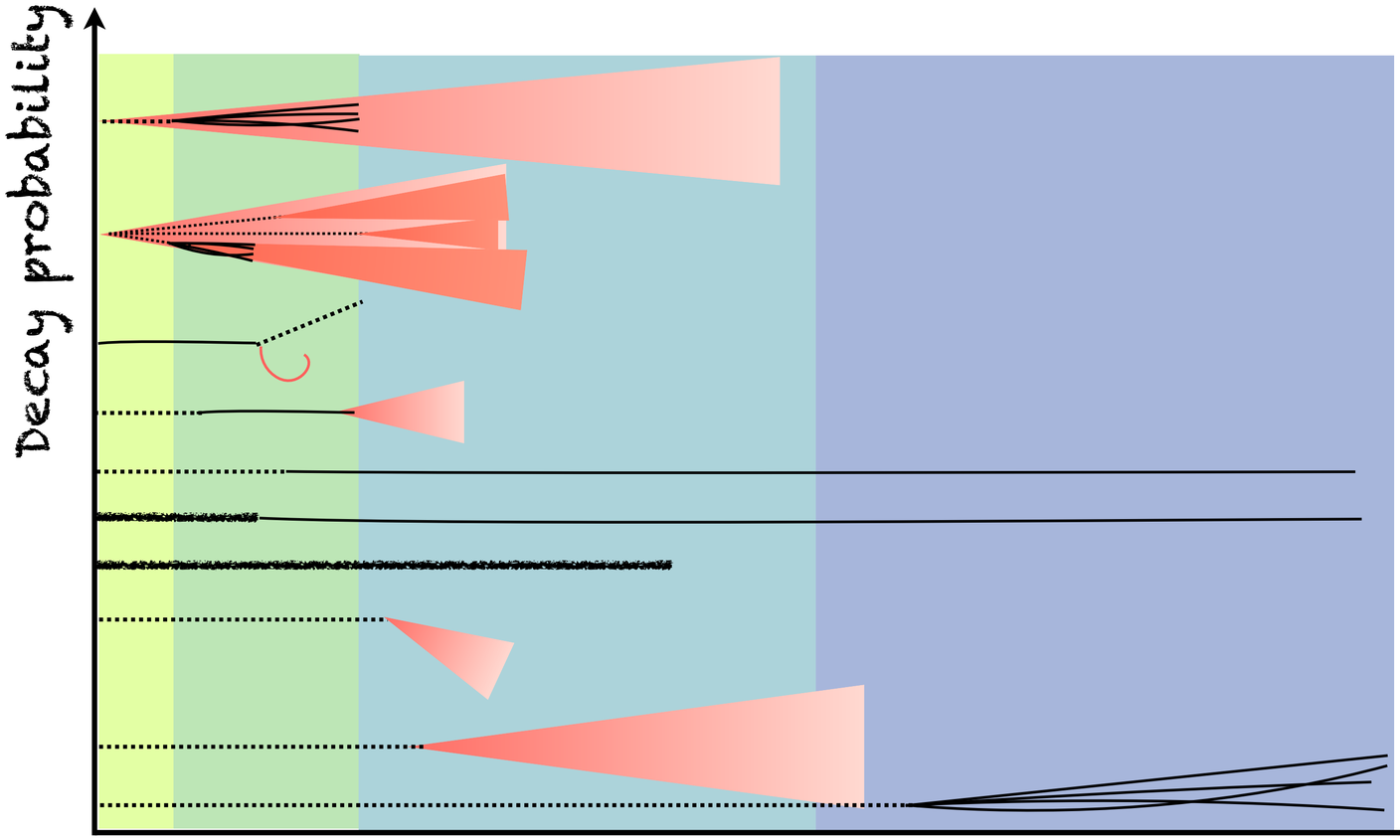
# Where should we look for LLPs in collider experiments?




Figures by H. Russell

# Where should we look for LLPs in collider experiments?

## How




- DV in the ID
- Semi-visible jets
- Emerging jets
- Disappearing tracks
- Displaced electrons / muons
- Unconventional ionization loss (Multiple, fractional, milli-charged)
- Non-pointing photons
- Displaced jets
- DV in the MS
- Delayed or slow-moving particles

We can use information from different sub detectors (or even different detectors!) for different targets

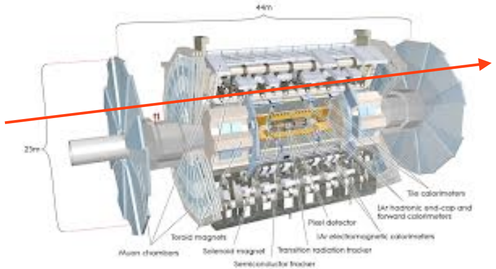
# How can we look for LLPs in collider experiments?

## A few challenges to take into account:

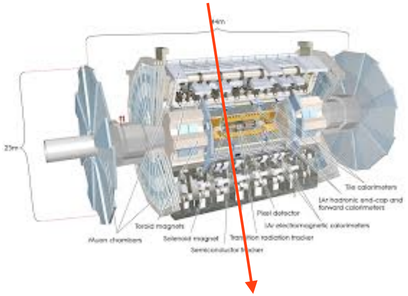
| Lifetime | LLP nature | Object Identification | Trigger | Background rejection | Systematic uncertainties |
|---|---|---|---|---|---|
| • Where does it decay? | • Electric charge<br>• Decay mode | • ATLAS, CMS: prompt objects<br>• New algorithms | • Standard triggers are not efficient<br>• Dedicated triggers | • Non-standard backgrounds<br>• No good MC<br>• Data-driven | • Recommendations non applicable<br>• New algorithms require syst. |

- ATLAS, CMS and LHCb have a broad program to search for LLPs
- Heavily increasing during the last few years
- New triggers, improved displaced track reconstruction, new object identification techniques, better unconventional background rejection, …

beam-induced-background

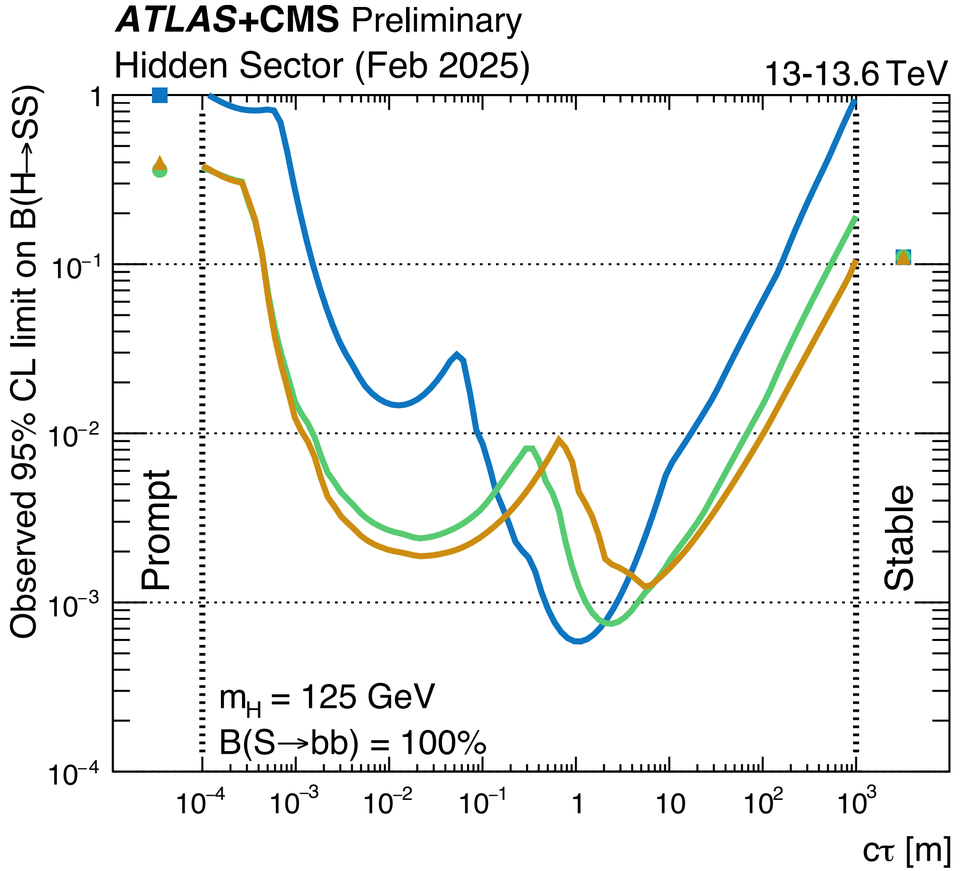


cosmic muons



# An intense decade…

## Hidden Sector models

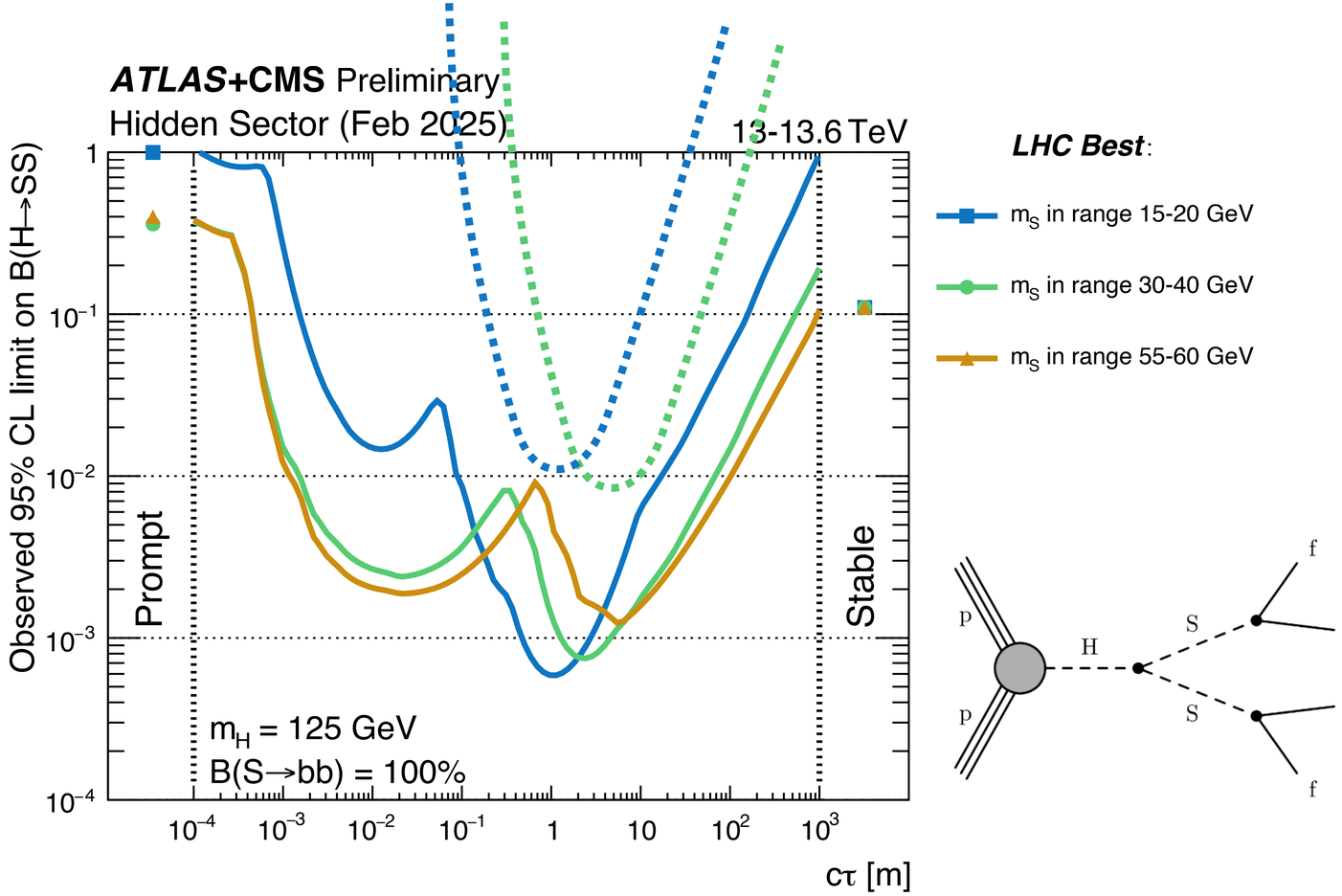


# An intense decade…

## Hidden Sector models

2015

- ATLAS Calorimeter displaced jets
- ATLAS MS displaced vertices



# An intense decade…

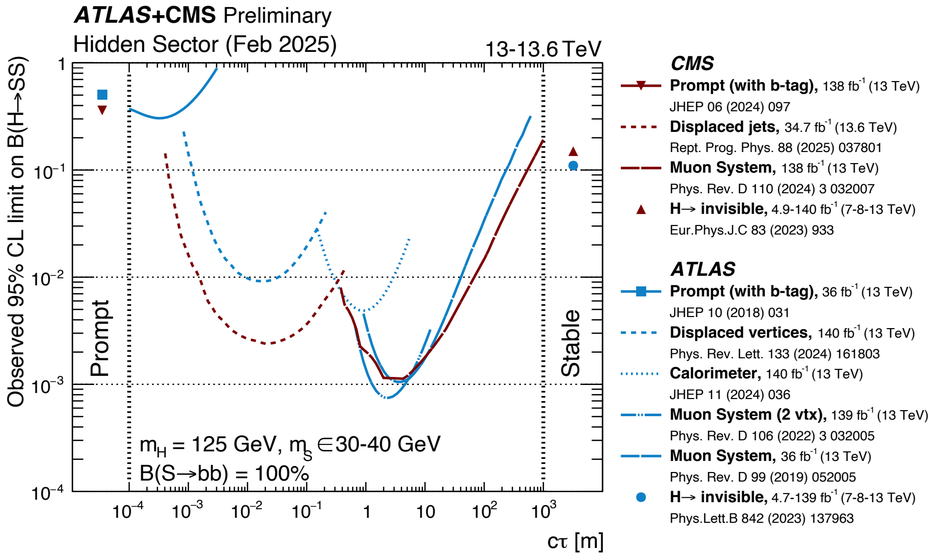
2015

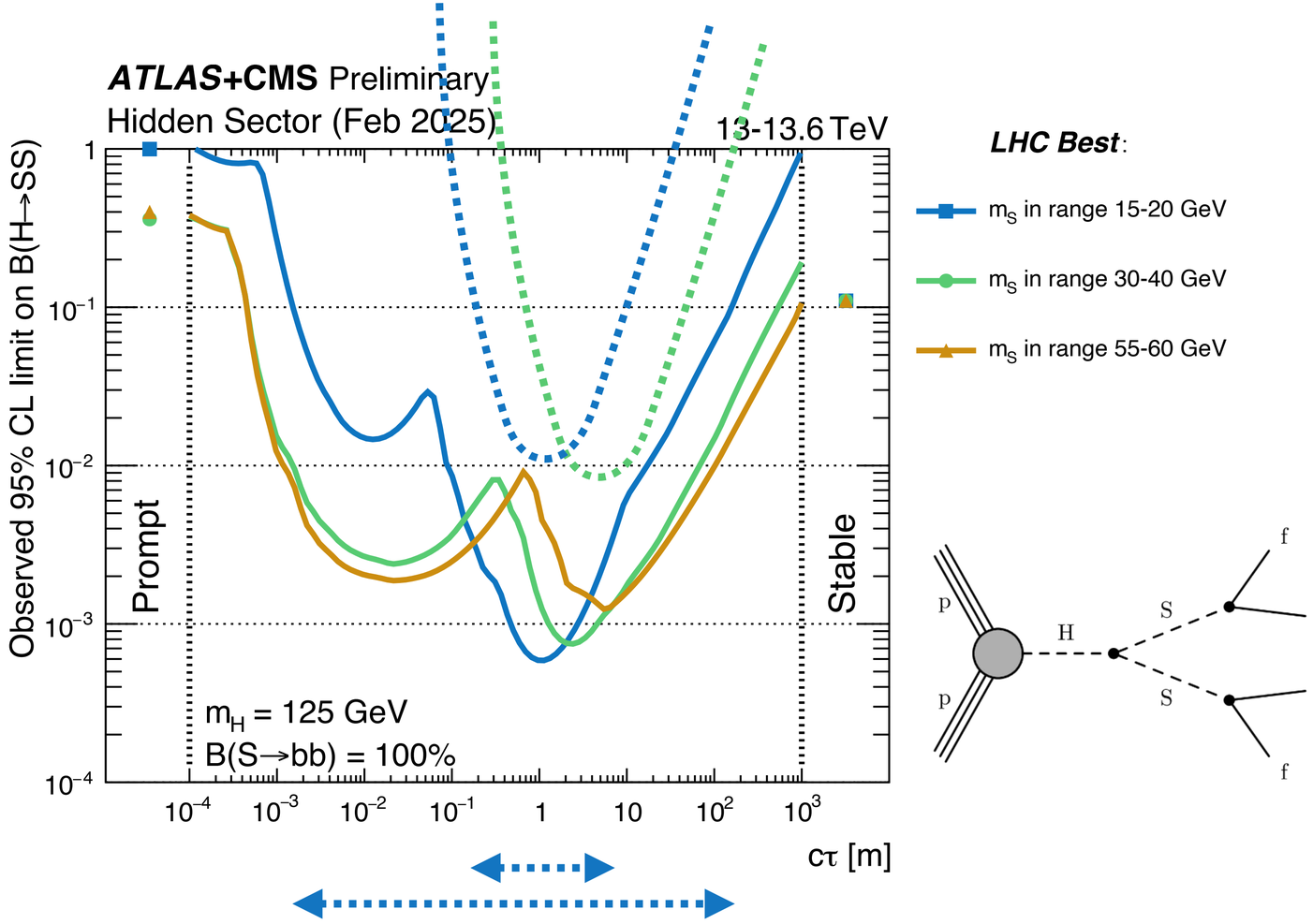
- ATLAS Calorimeter displaced jets
- ATLAS MS displaced vertices

## Hidden Sector models

- ATLAS prompt b-jet
- ATLAS ID DV
- ATLAS Calorimeter DJ
- ATLAS MS DV
- ATLAS H -> invisible

- CMS prompt b-jet
- CMS ID DV
- CMS MS DV
- CMS H -> invisible



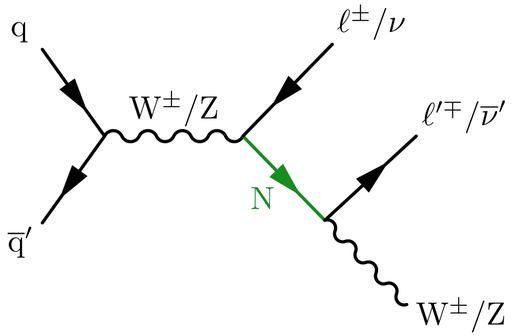



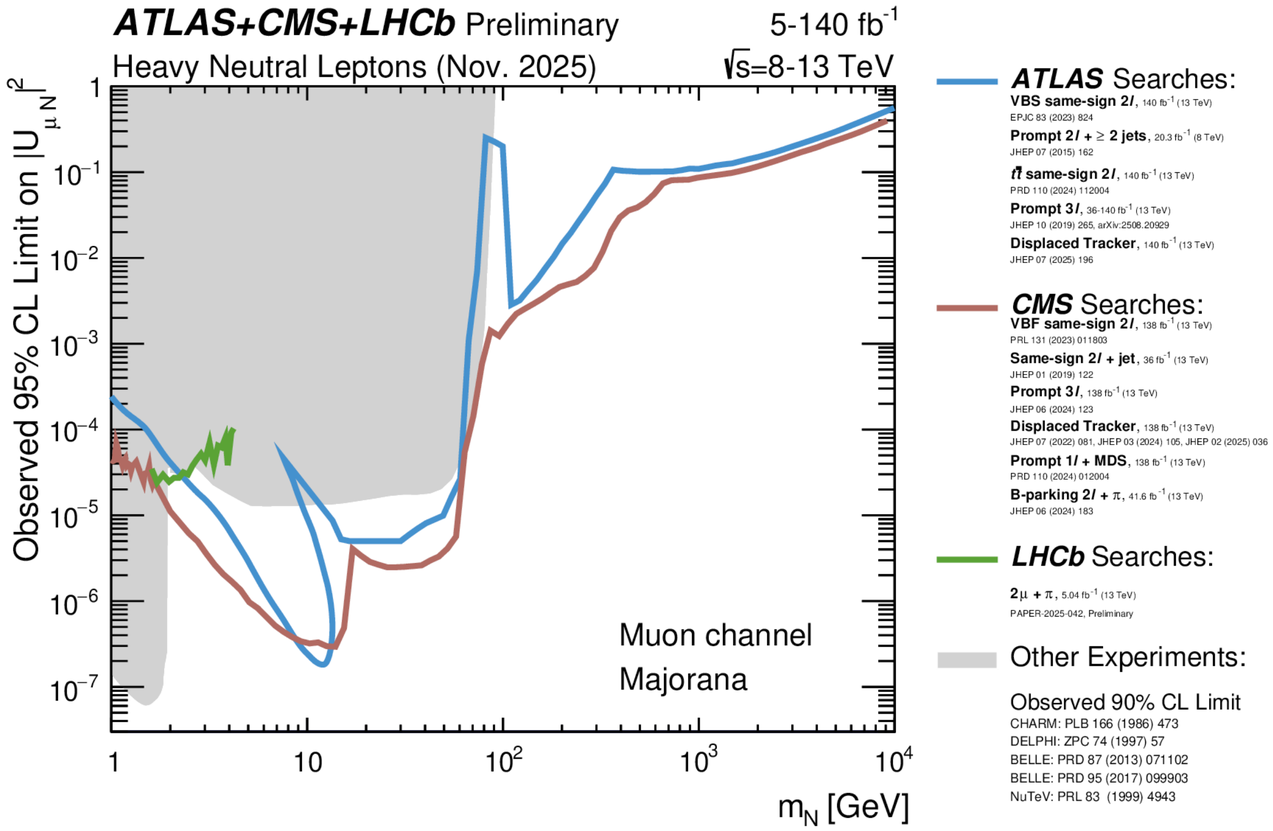

Extended lifetime coverage by 4 orders of magnitude

Extended sensitivity by 1 order of magnitude

# An intense decade…

## Heavy Neutral Leptons



# An intense decade…

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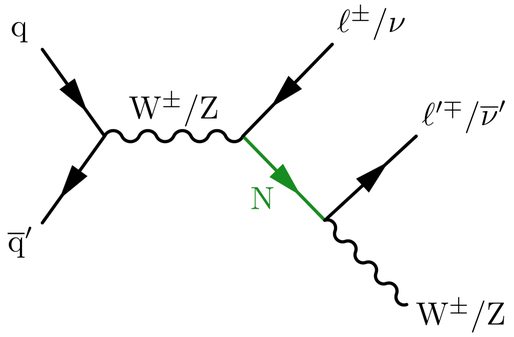
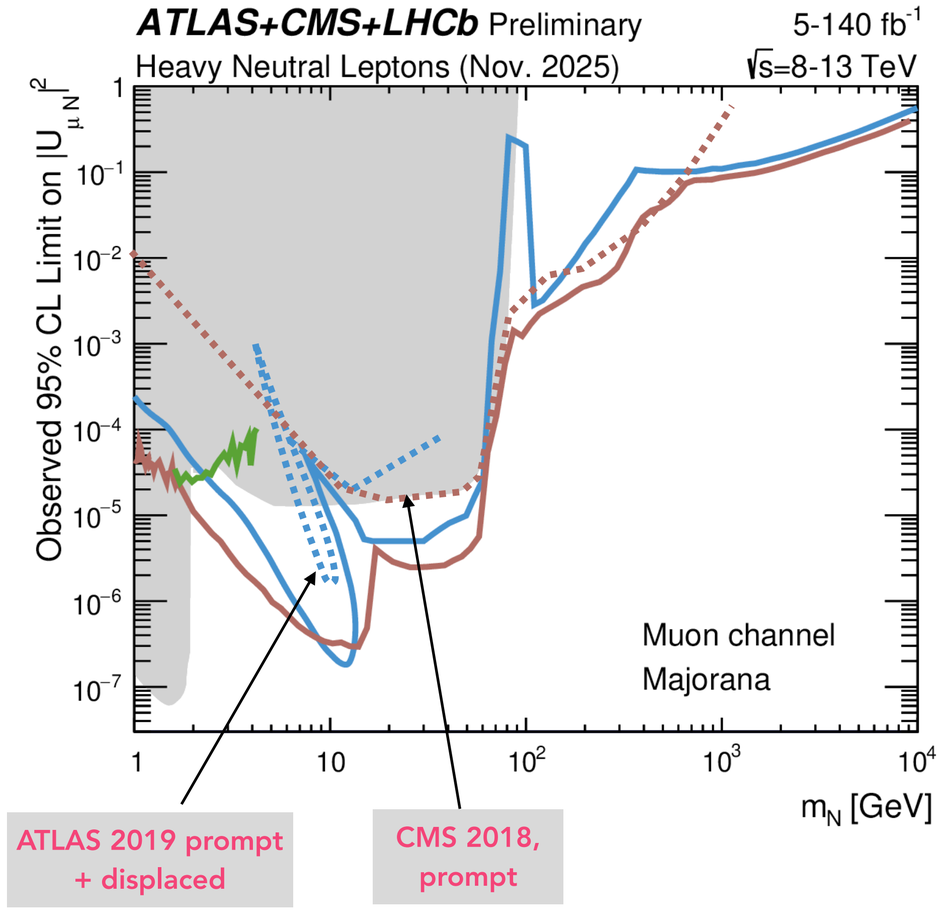
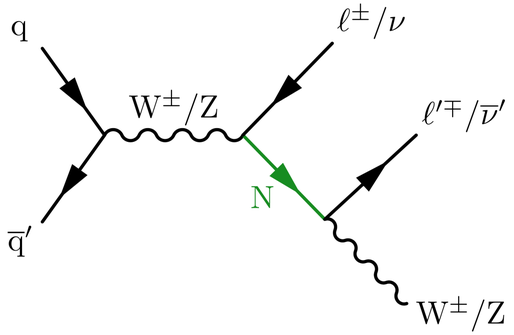


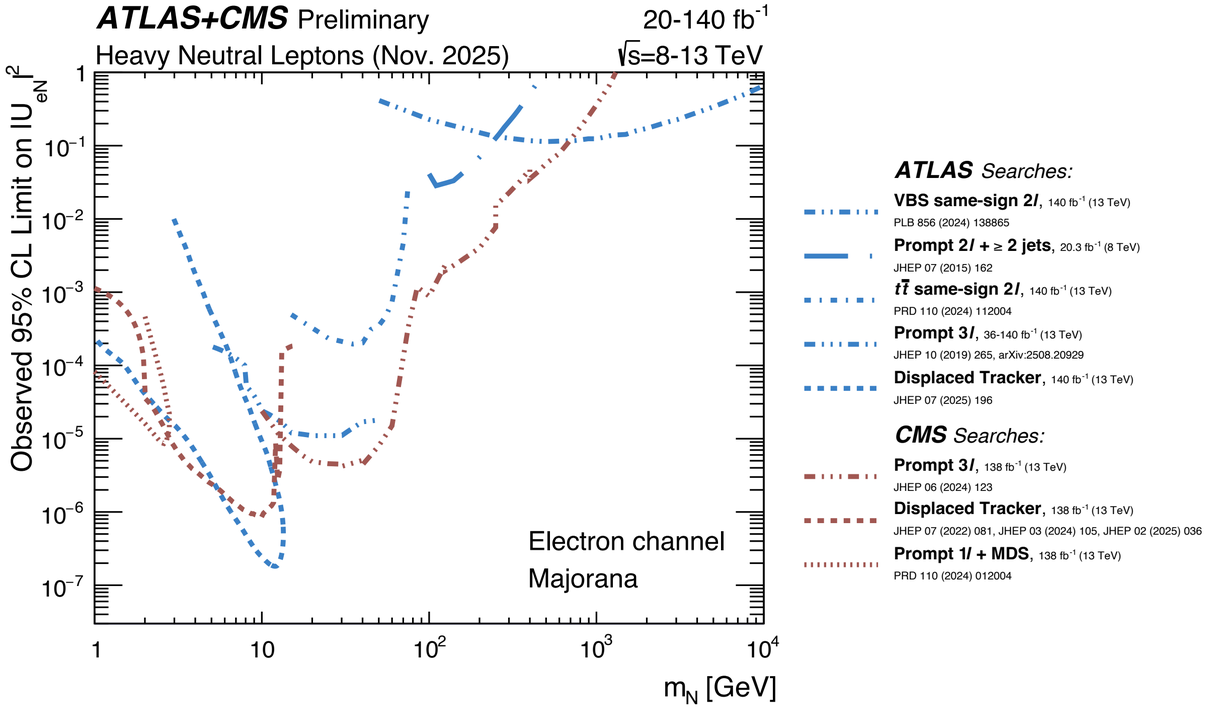



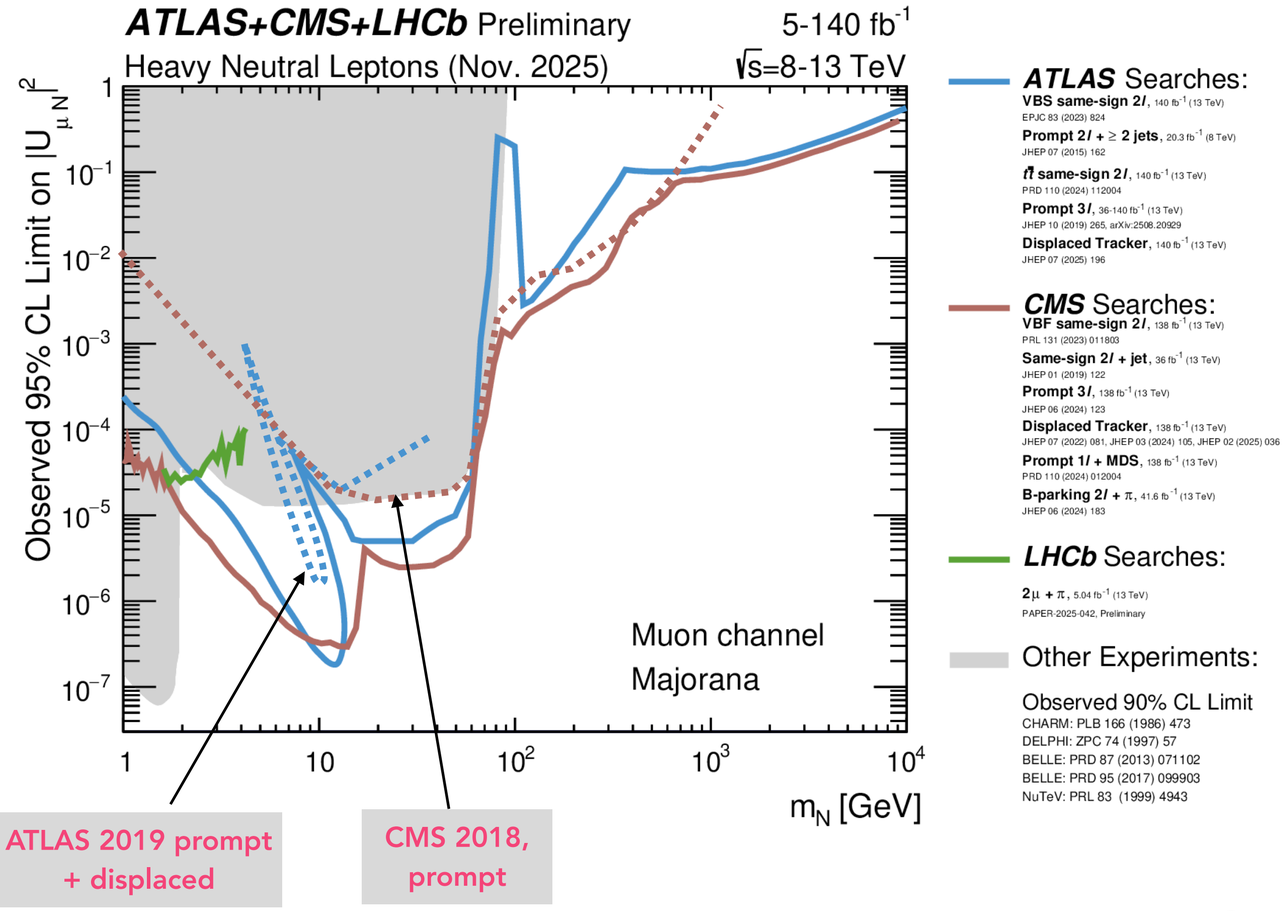
# An intense decade…

## Heavy Neutral Leptons

- ATLAS prompt 2l / 3l
- ATLAS ID DV
- LHCb 2 mu
- CMS prompt 1l / 2l / 3l
- CMS ID DV
- CMS MDS
- CMS B-parking 2l



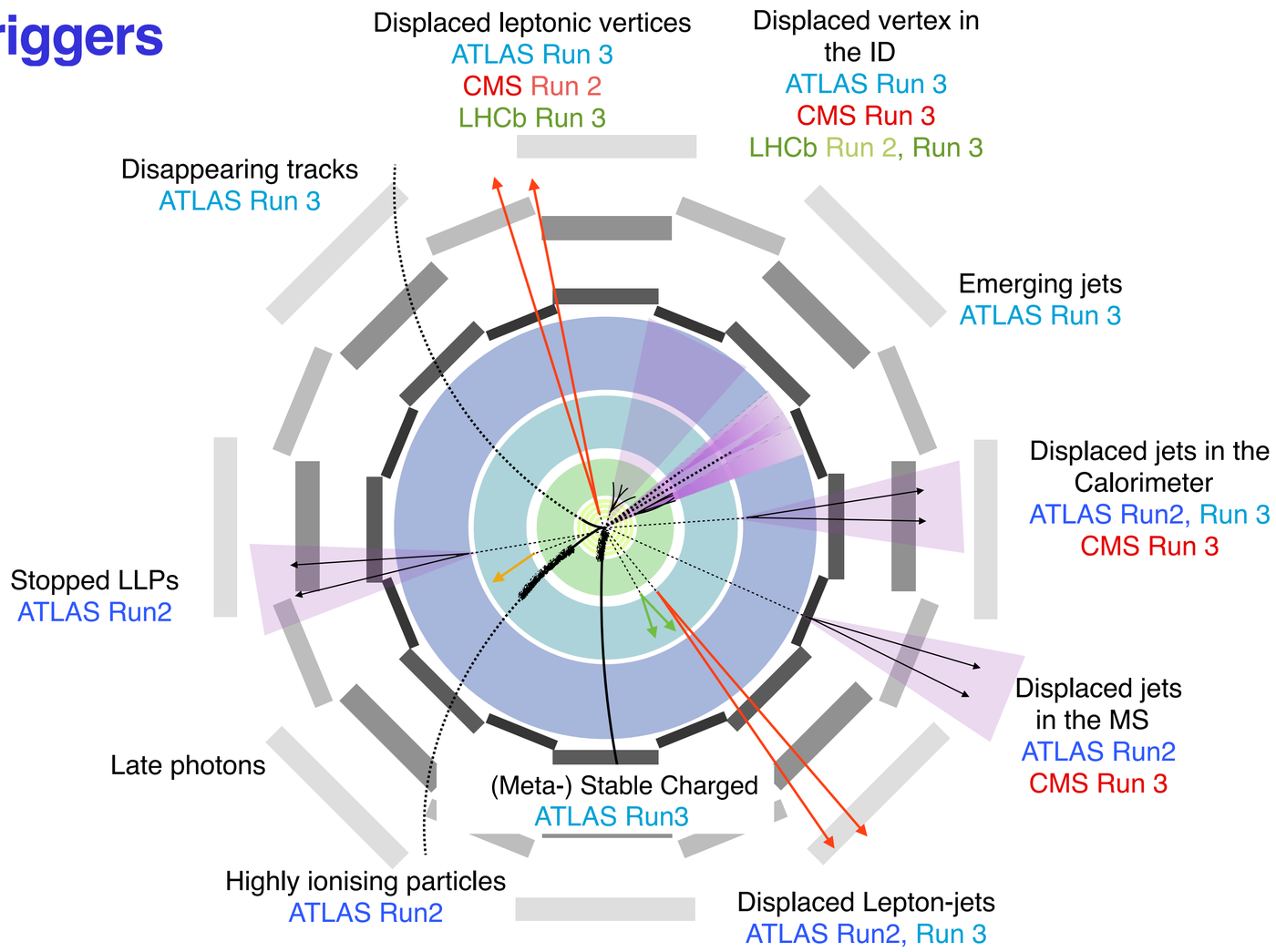



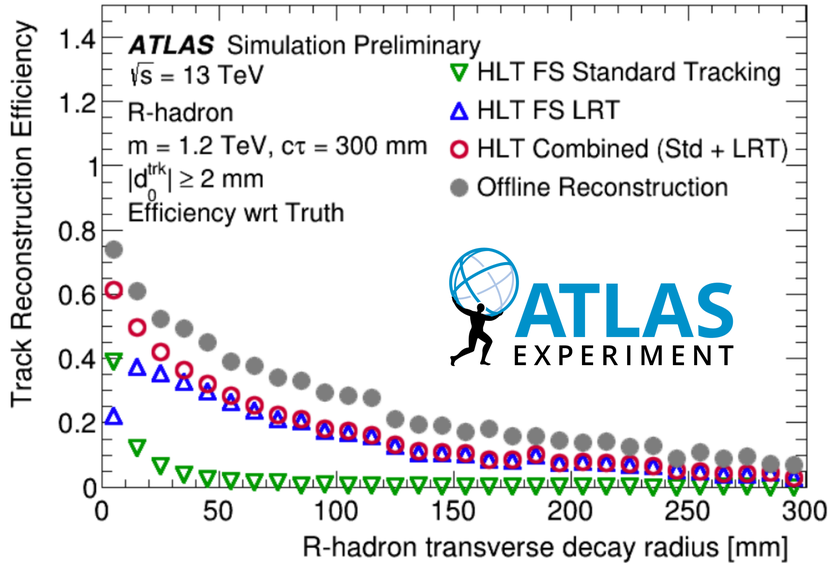



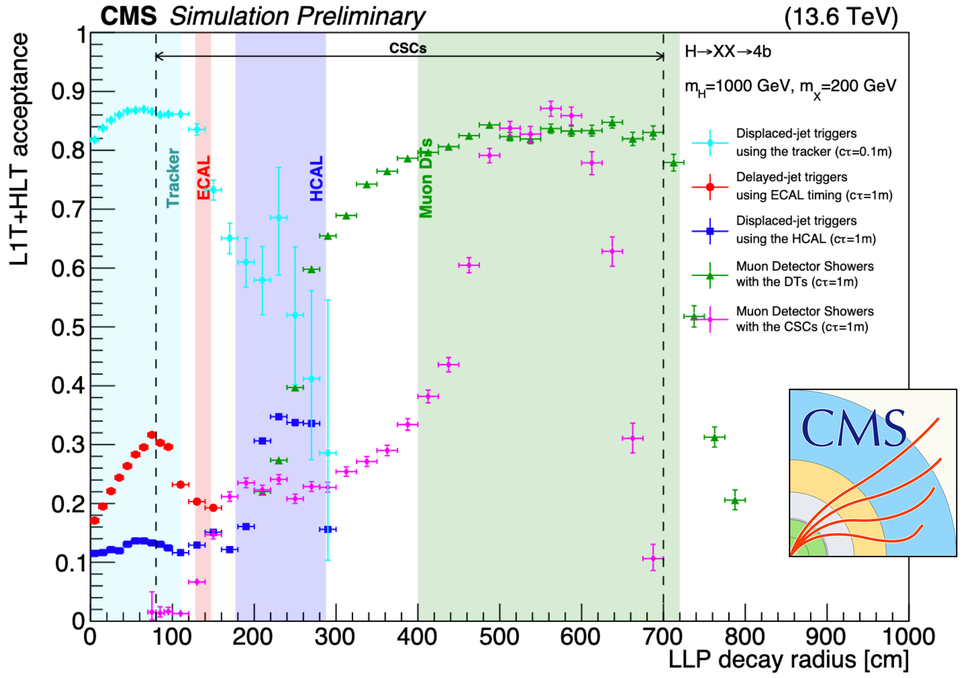

2 orders of magnitude increase in sensitivity since 2018

# An intense decade…

## Triggers



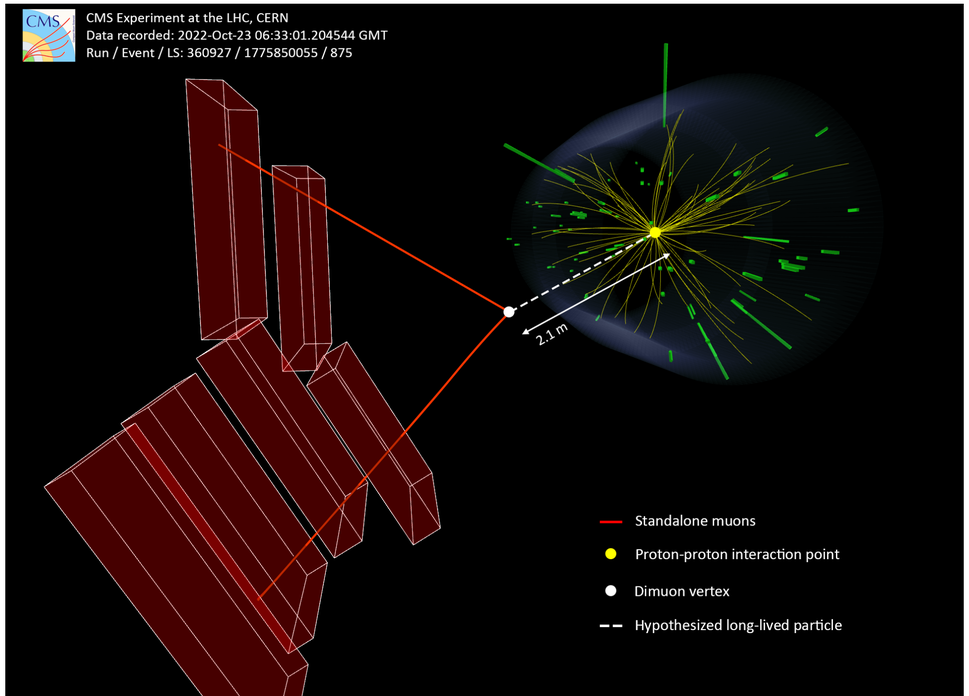




ATLAS Run 3 LLP triggers: https://arxiv.org/pdf/2401.06630
CMS Run 3 LLP triggers: http://cds.cern.ch/record/2937649

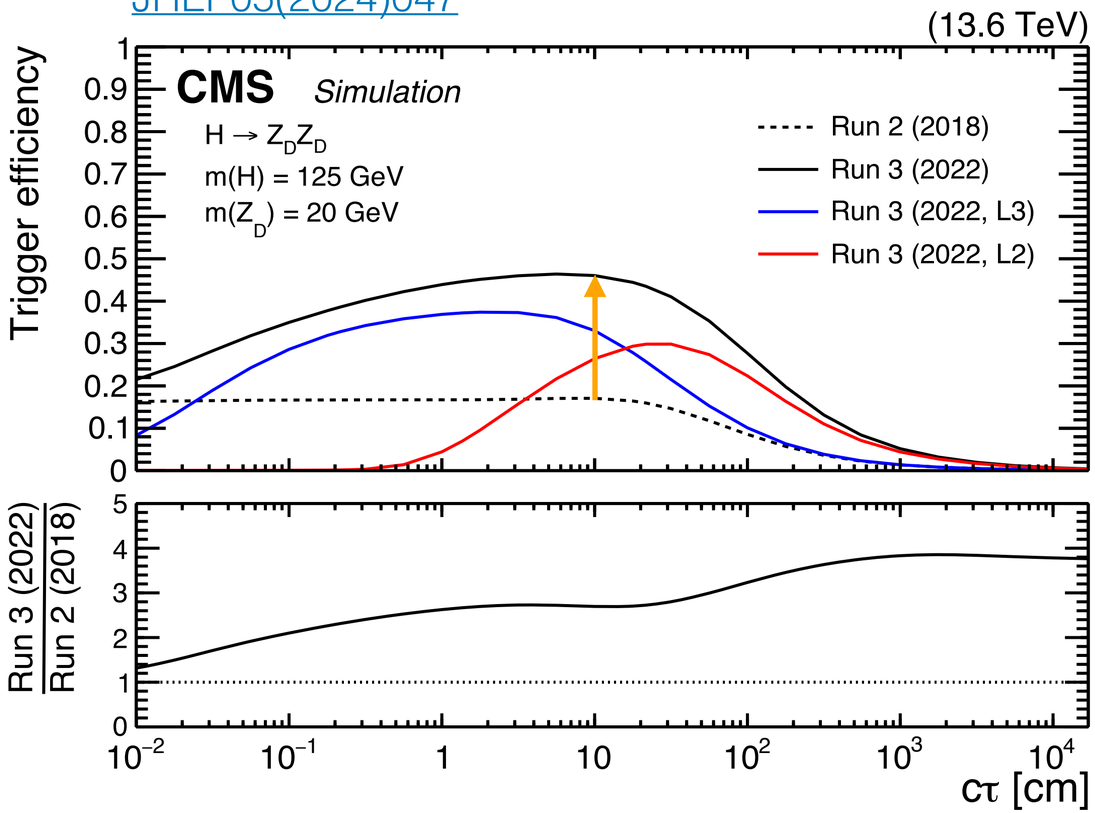
# An intense decade…

## LLP Trigger example at CMS

- **Di-muon trigger** produced within and after the tracker
  - Run 2: 2 muons in the Muon system only, including beamspot constraint
  - Run 3: two additional L1 triggers for a
    - OS muon pair with low pT (4.5 GeV) and small dR
    - New track-finder w/o beamspot constraint, higher pT



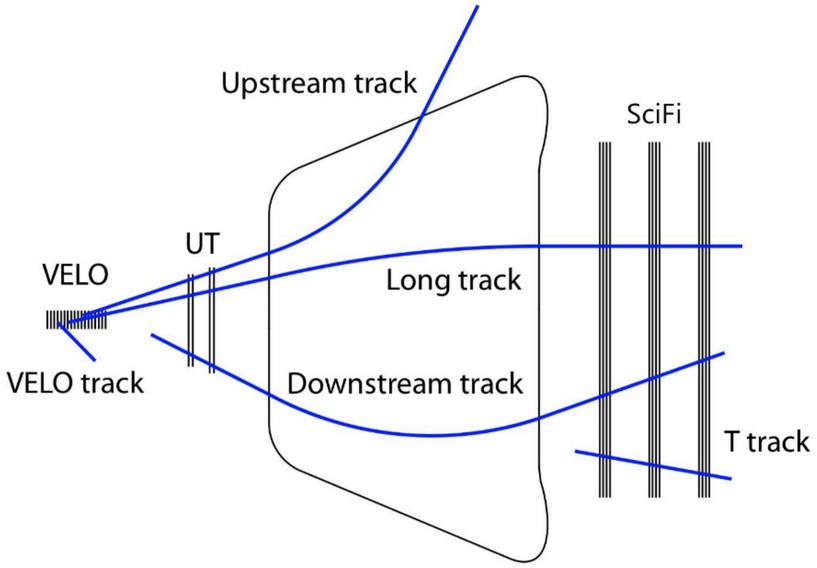

JHEP05(2024)047

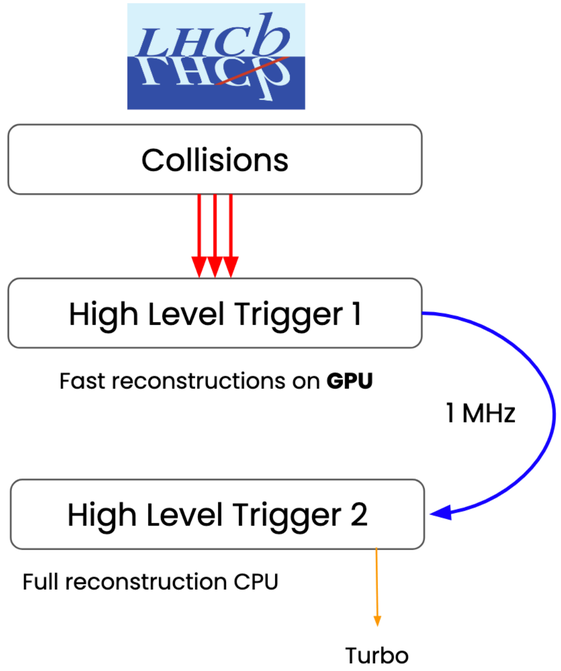


# An intense decade…

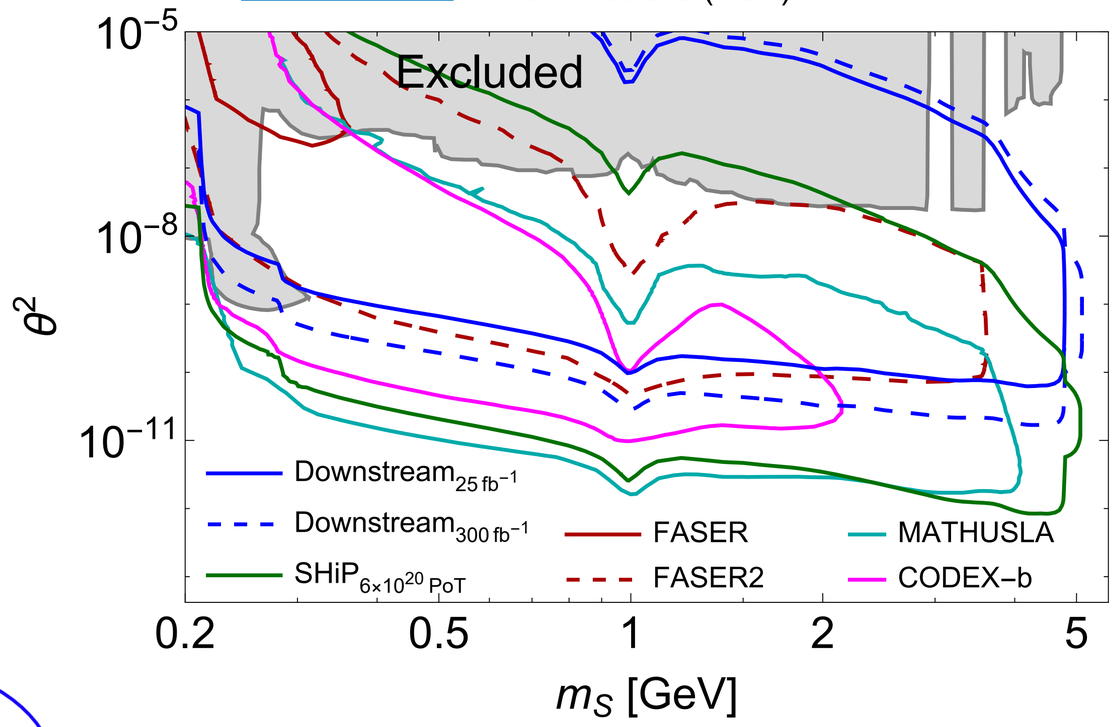
## LLP Trigger example at LHCb

- LLPs can be reconstructed with Downstream tracks
- Run 2: Downstream tracking couldn't be implemented in HLT1 due to limit timing budgets.
- Run 3: GPU version of Downstream tracking! running in data-taking since the end of 2024




2503.23087 Dark scalars (BC4)



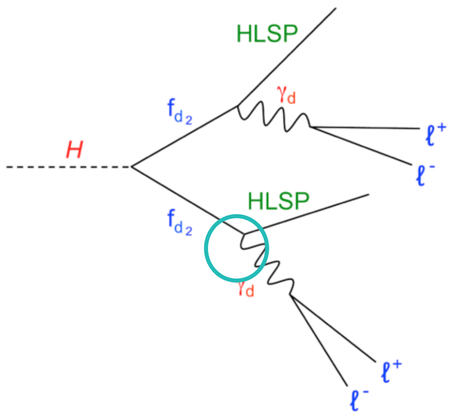
# An intense decade…

## Machine Learning

- Displaced objects can be difficult to identify from weird backgrounds (detector effects, BIB, cosmics, material interactions
- ML is here to help!!

## LLP ML example at ATLAS

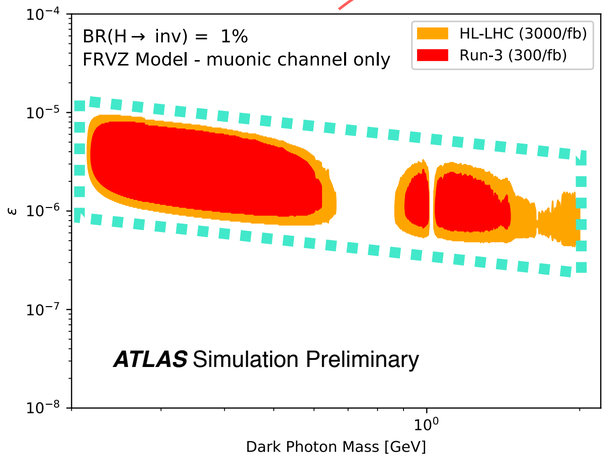
- Search for displaced dark photon jets




Wrt original (2015): x10 lumi

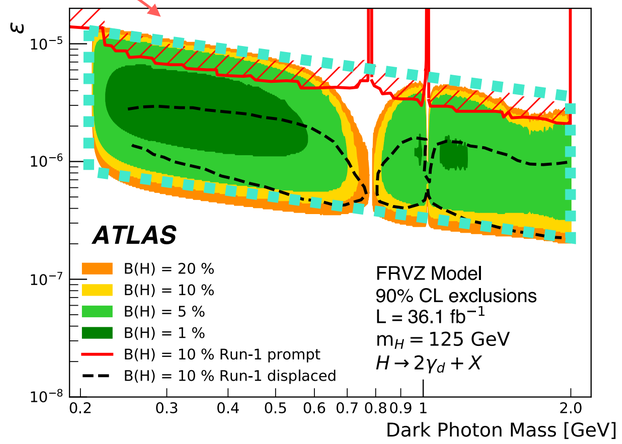
Identification of dark photons:

Cut-based → BDT




ATL-PHYS-PUB-2019-002
Projection from
ATLAS-CONF-2016-042

(2015 data)




Eur. Phys. J. C 80 (2020) 450

(2016 data)

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## LLP ML example at ATLAS

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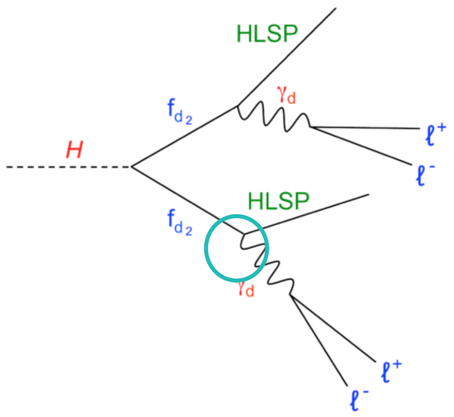
Use of ML in displaced jets reconstruction:

50x increase of sensitivity in 5 years!




Wrt original (2015): x10 lumi

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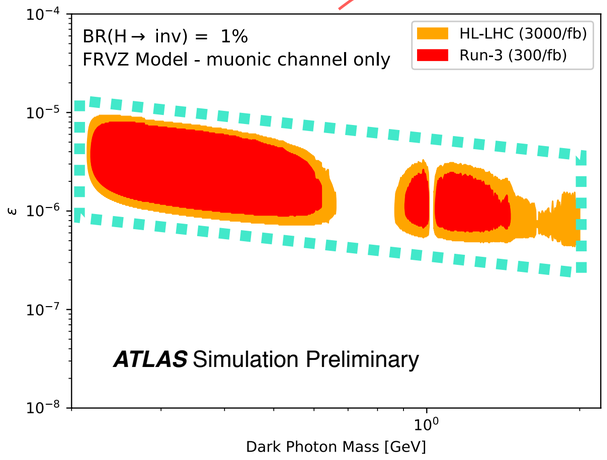
Cut-based → BDT




ATL-PHYS-PUB-2019-002

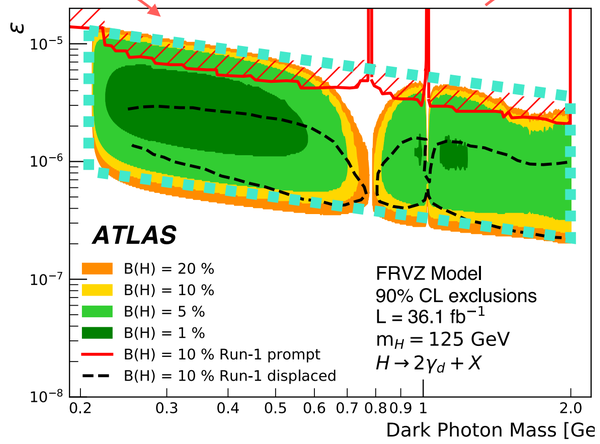
Projection from ATLAS-CONF-2016-042

(2015 data)

Wrt previous analysis (2016): x4 lumi

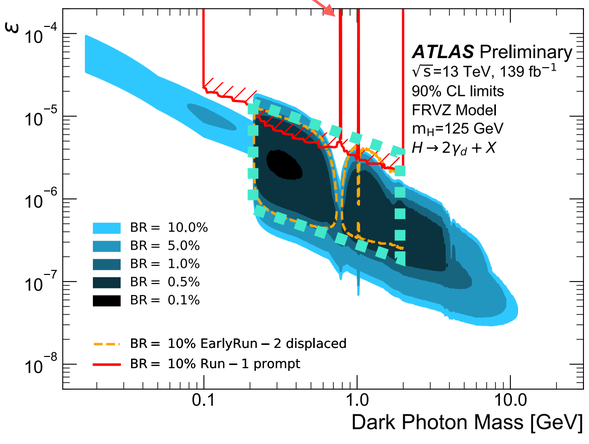
Identification of dark photons:

BDT → DNN




Eur. Phys. J. C 80 (2020) 450

(2016 data)




ATLAS-CONF-2022-001

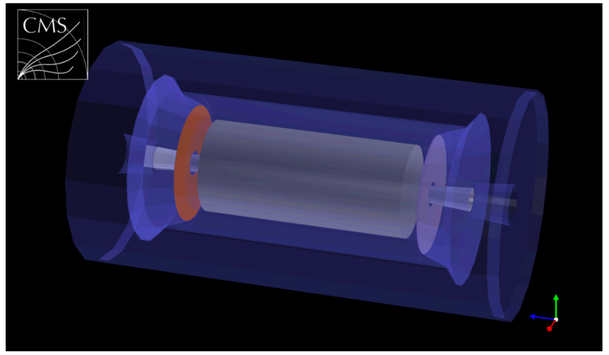
Full Run 2

# An intense decade to come!

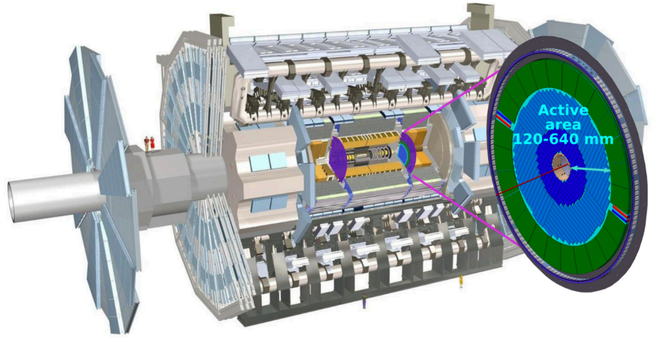
## Upgrades advantages for LLPs

- **Precision Timing Detectors**
  - Resolution of 30ps (50ps)!!
  - Better **pileup** and **beam-induced-background** rejection
  - Better beta measurements

CMS MIP Timing Detector (MTD)

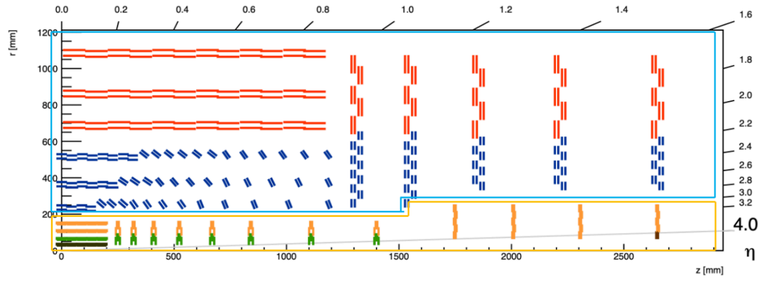



ATLAS High Granularity Timing Detector (HGTD)

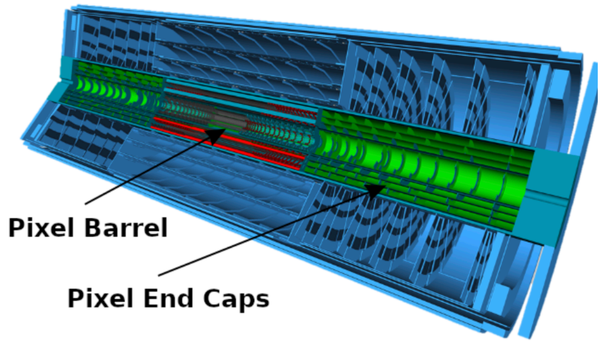



- **All silicon trackers**
  - Extended coverage up to $|\eta| = 4$
  - Impact on DV and disappearing tracks
  - Track veto for displaced jets
  - **CMS Tracking info at L1**

CMS Tracker

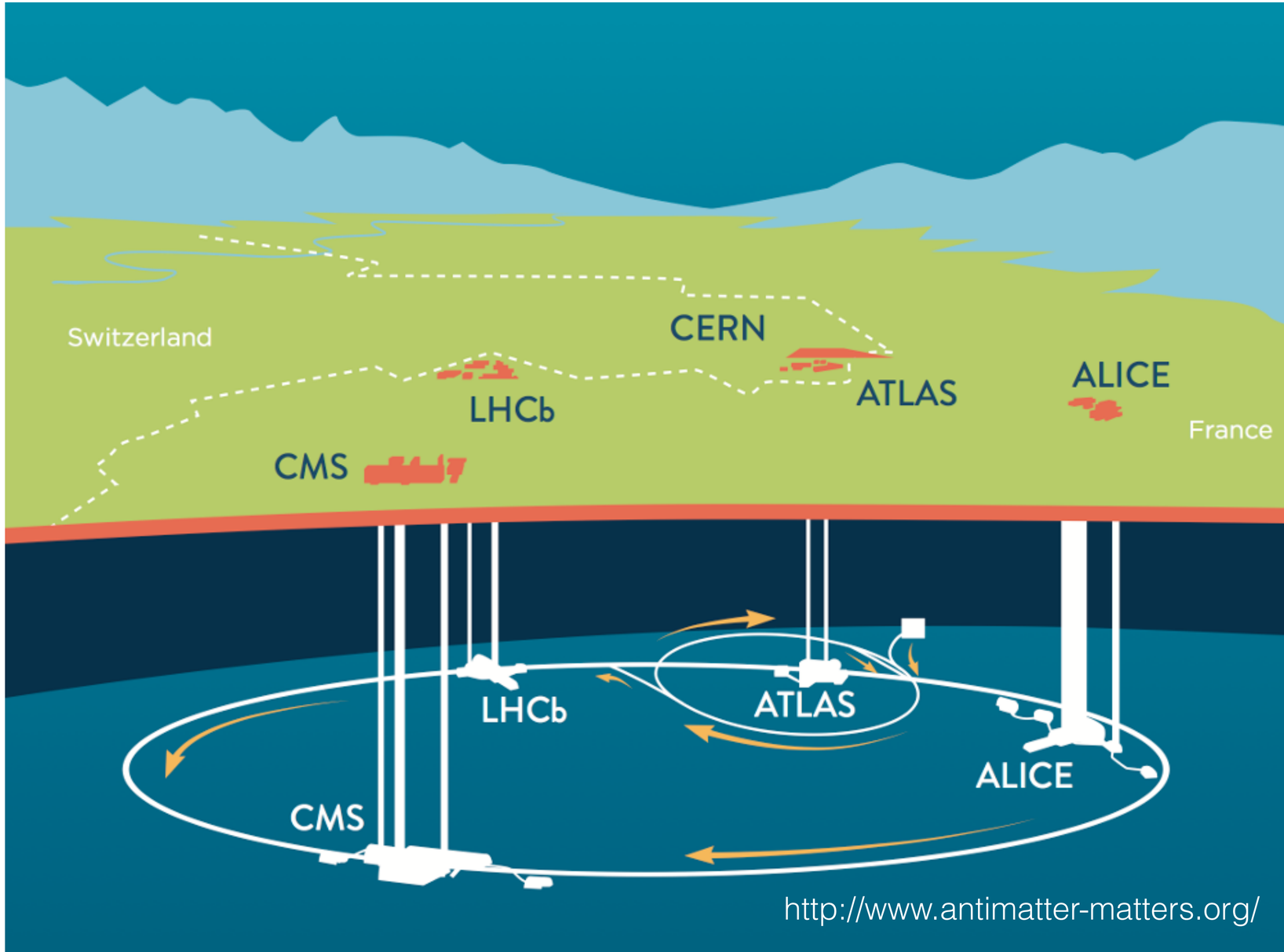



ATLAS Inner Tracker (ITk)



# Dedicated experiments at the LHC

- Range of possibilities in LLP phenomenology is huge
- Different models, couplings, masses, decay modes, lifetimes, etc.
- Impossible to cover all of them with only one dedicated experiment!



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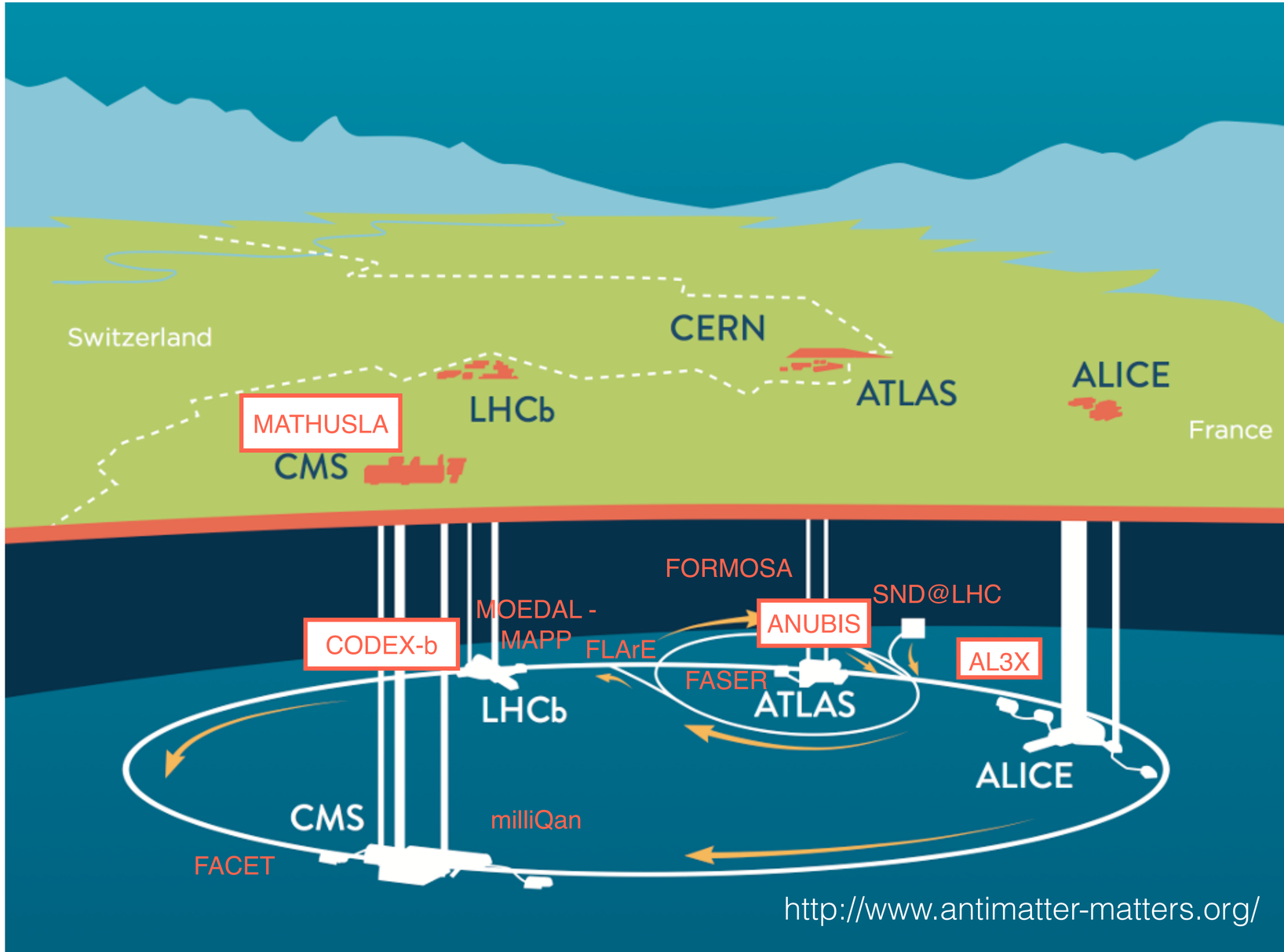


http://www.antimatter-matters.org/

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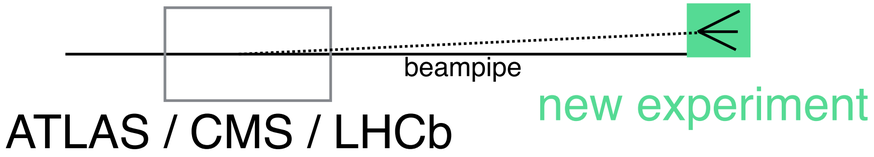
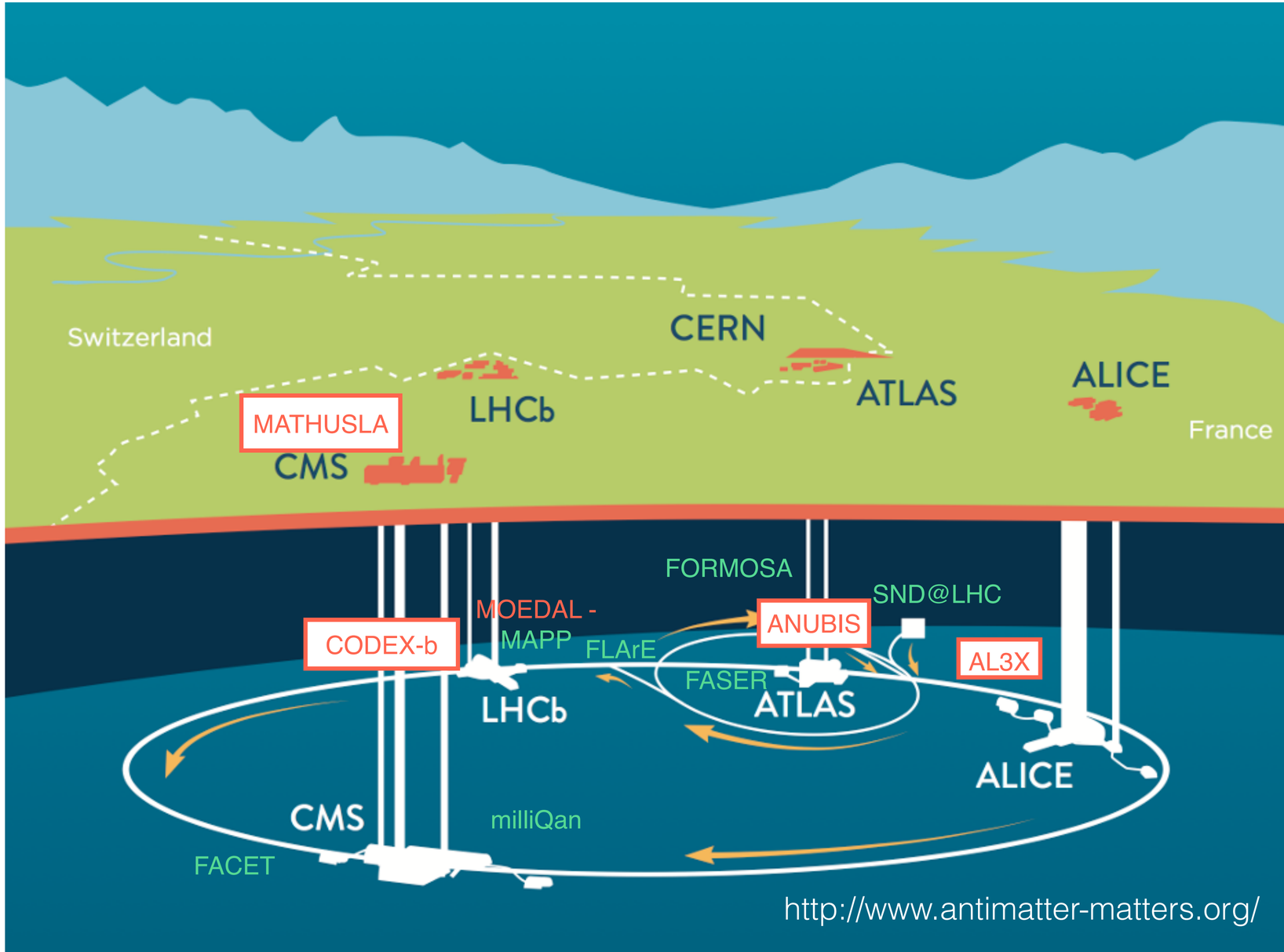
- Forward detectors:
- Search for very weakly coupled light particles: light mediators, ALPs



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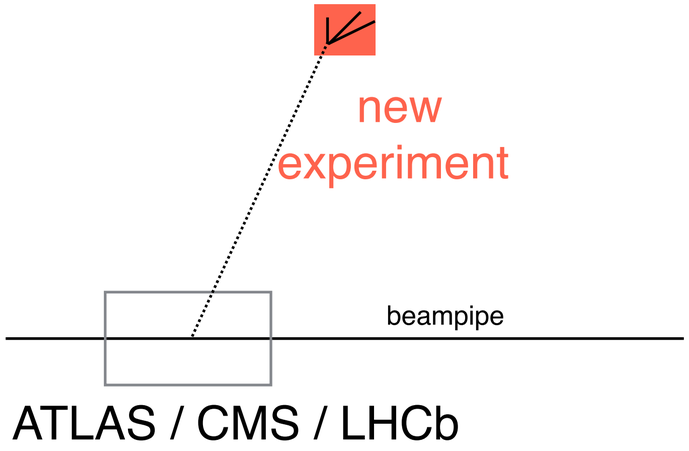
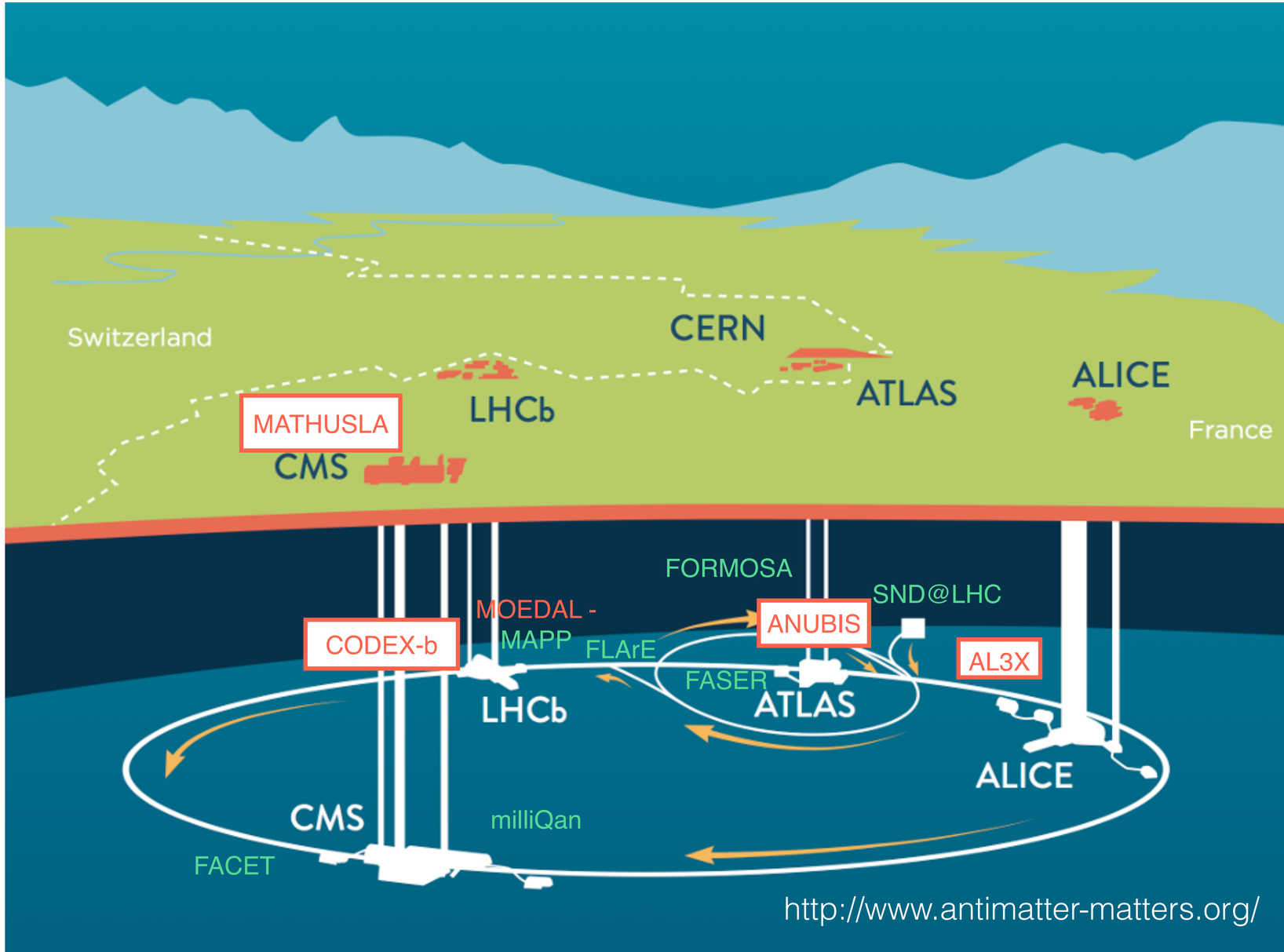
  - Transverse detectors:
  - Heavier LLPs, heavier mediators



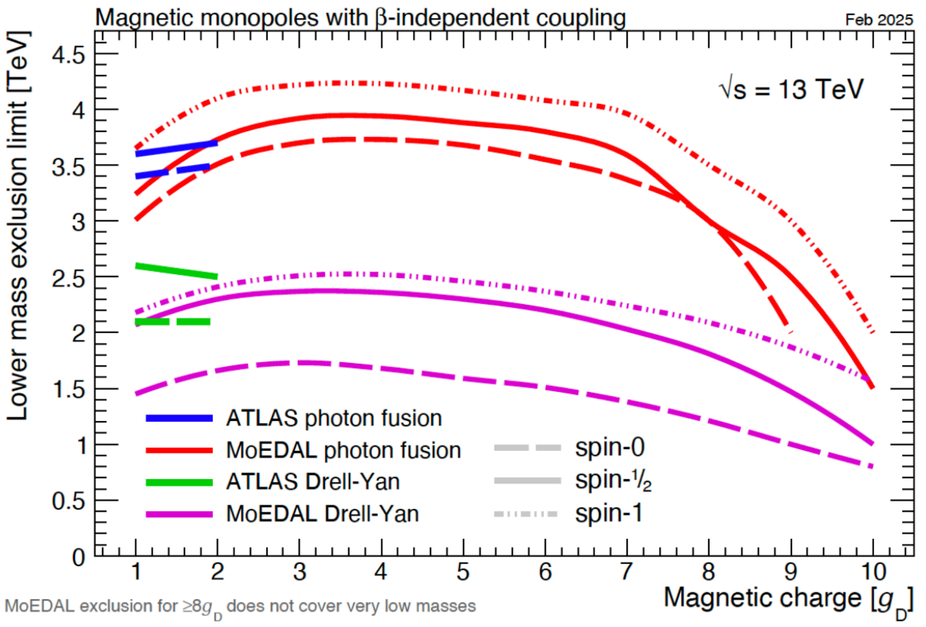
# Ongoing dedicated experiments

@ Emanuela Musumeci, Thurs 9:00

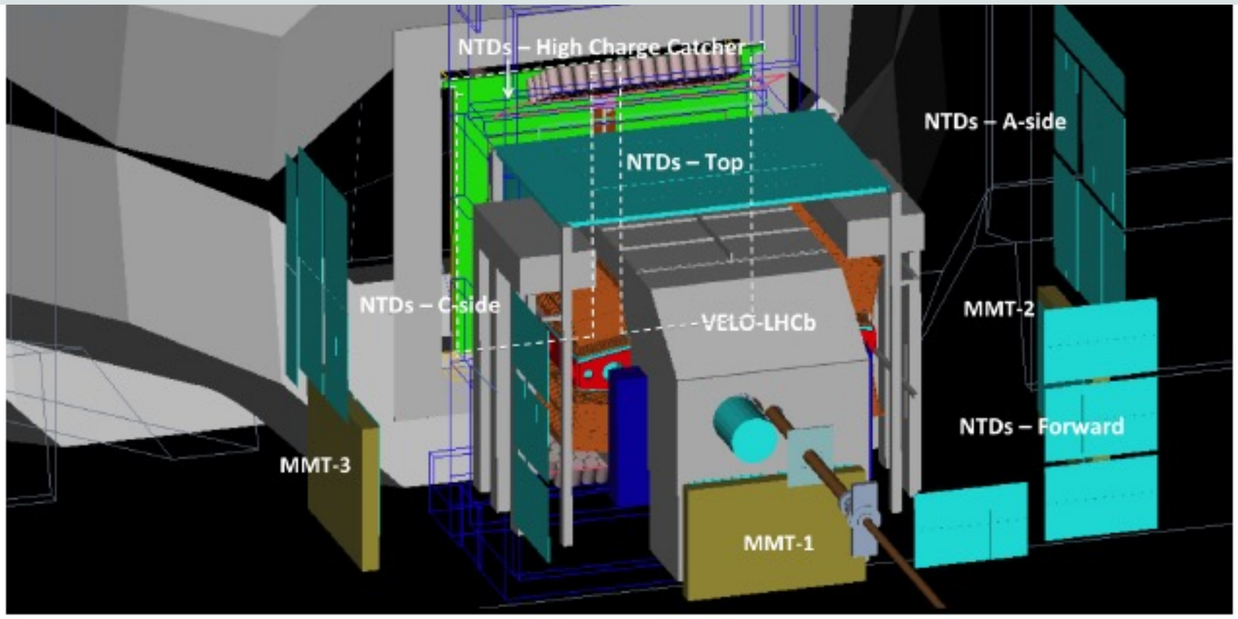
## MOEDAL

- Located at LHCb cavern, approved in 2010
- Target: **highly ionizing particles, magnetic monopoles**
  - Nuclear Track Detectors: HIP create damage along their track
  - Magnetic Monopole traps: bind a magnetically charged particles and capture it inside the atomic lattice
- No SM backgrounds!!
- Passive detectors: no trigger, no read-out

PRL 134 (2025) 071802




- Most stringent limits on monopoles

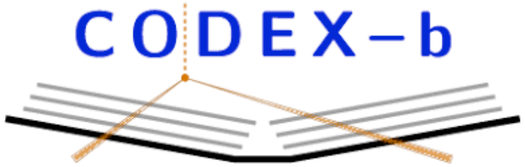



- MAPP (Run3): FIPs / LLPs milli-charged particles
  - Forward direction, ~100m away from IP (rock shielding)

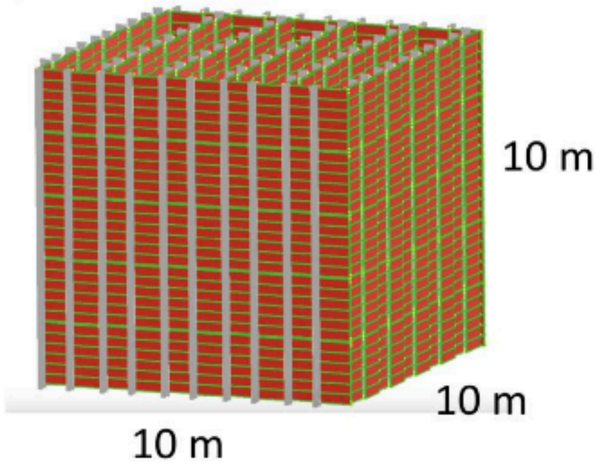
# Future dedicated experiments

@ Carlos Vázquez, Weds 18:20

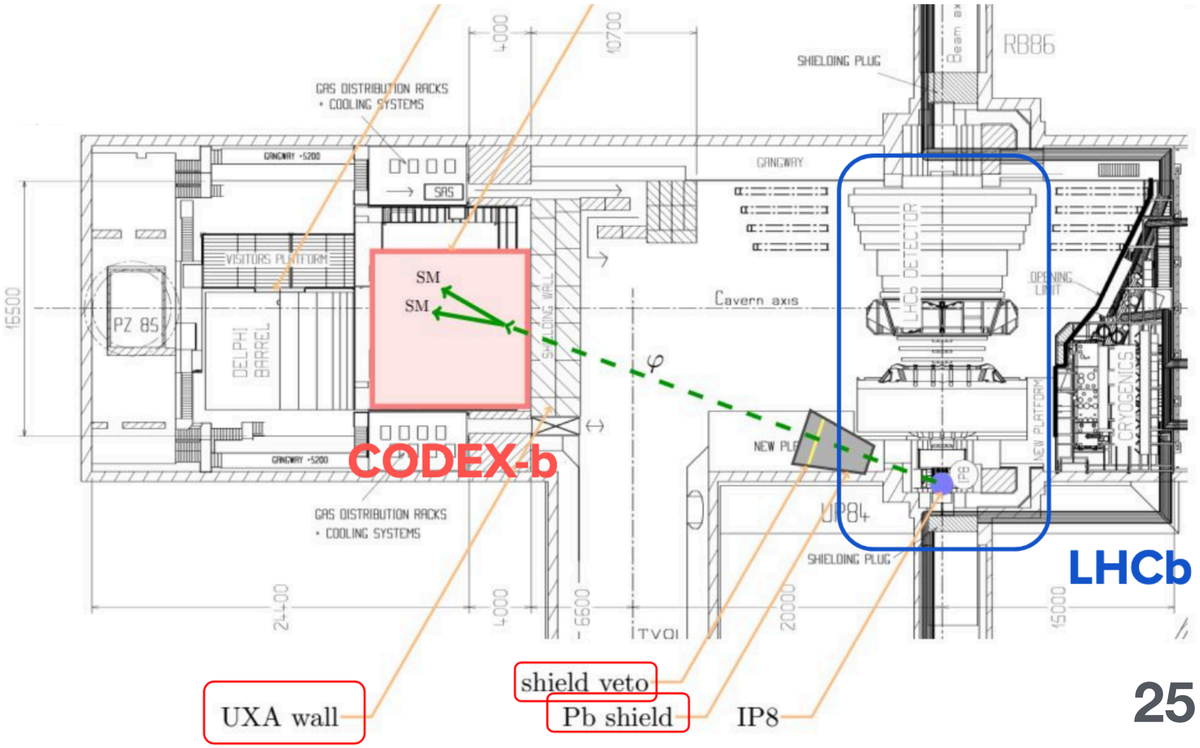
## CODEX-b (β)




- Objective: **long-lived particles**
- Located at 25m distance from LHCb
- Concrete wall + shield veto against collision background
  - Codex-β demonstrator (2m x 2m x 2m) for 2026 data taking




Resistive Plate Chamber (RPC) detectors assembled in triplets



# Future dedicated experiments

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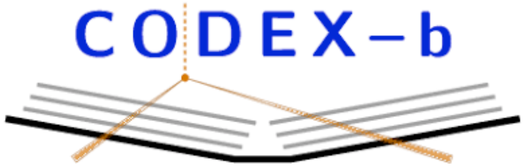


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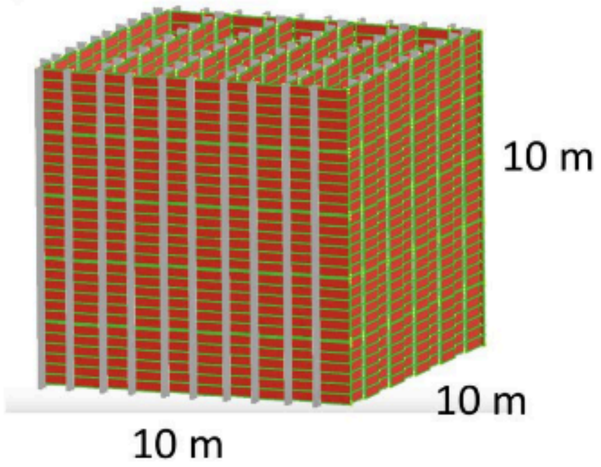
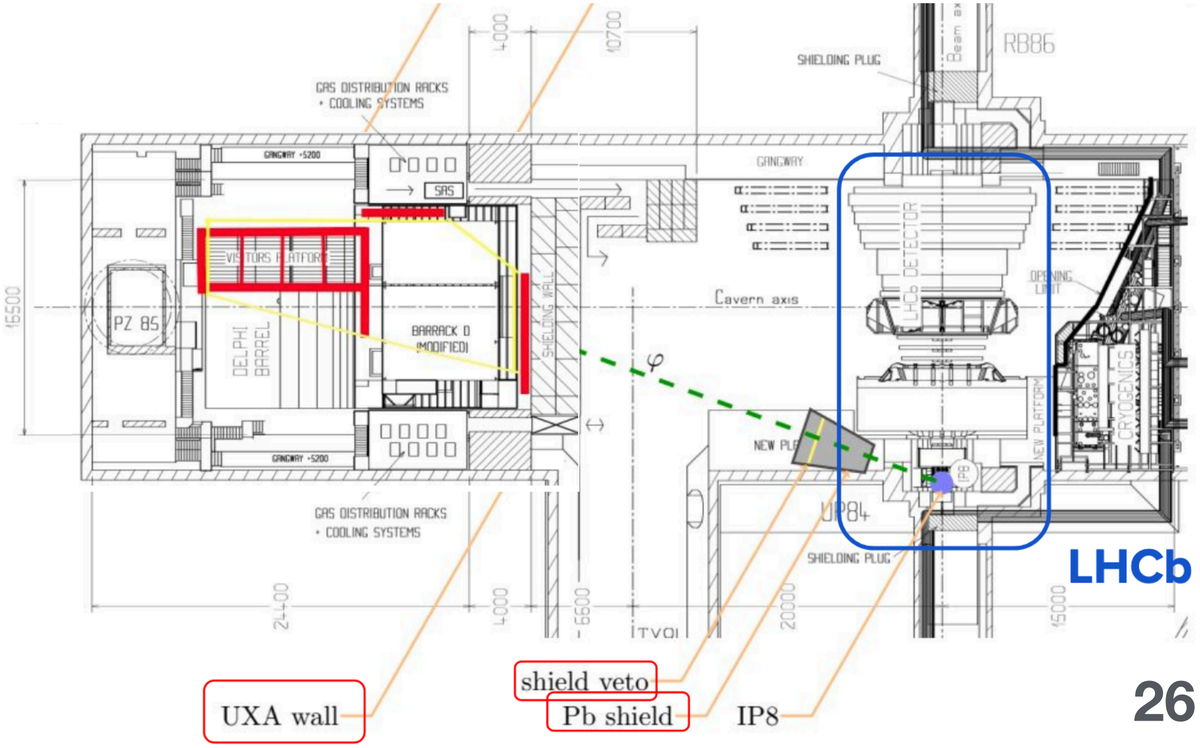



Resistive Plate Chamber (RPC) detectors assembled in triplets

Move from RPCs (gas flow) to sealed RPCs (no flow)?

- Original cavern (LHCb trigger farm) no longer available!!
- Various new scenarios discussed (arXiv:2505.05952)
- Aim to converge by summer 2026, with a series of proposals to be studied by the LHCb after Run 3.

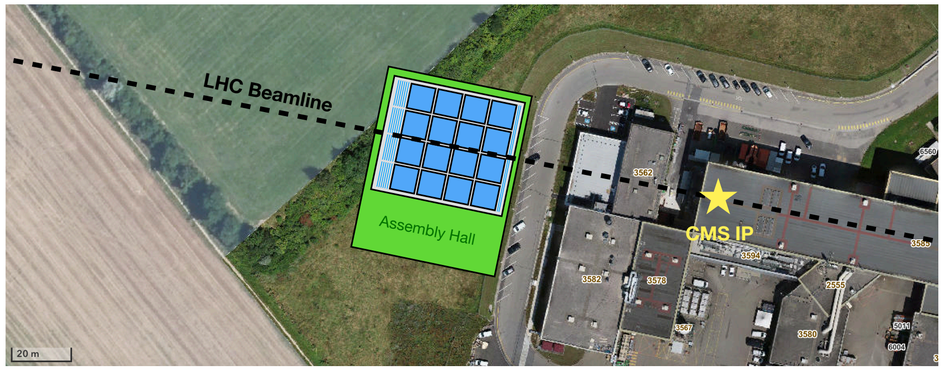


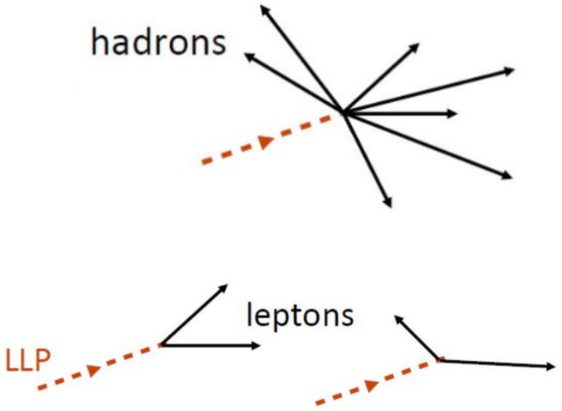
# Future dedicated experiments

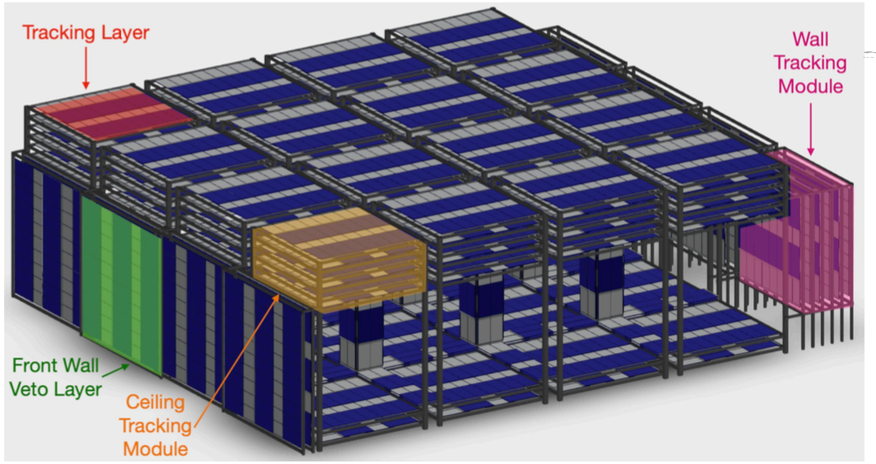
https://mathusla-experiment.web.cern.ch

## MATHUSLA

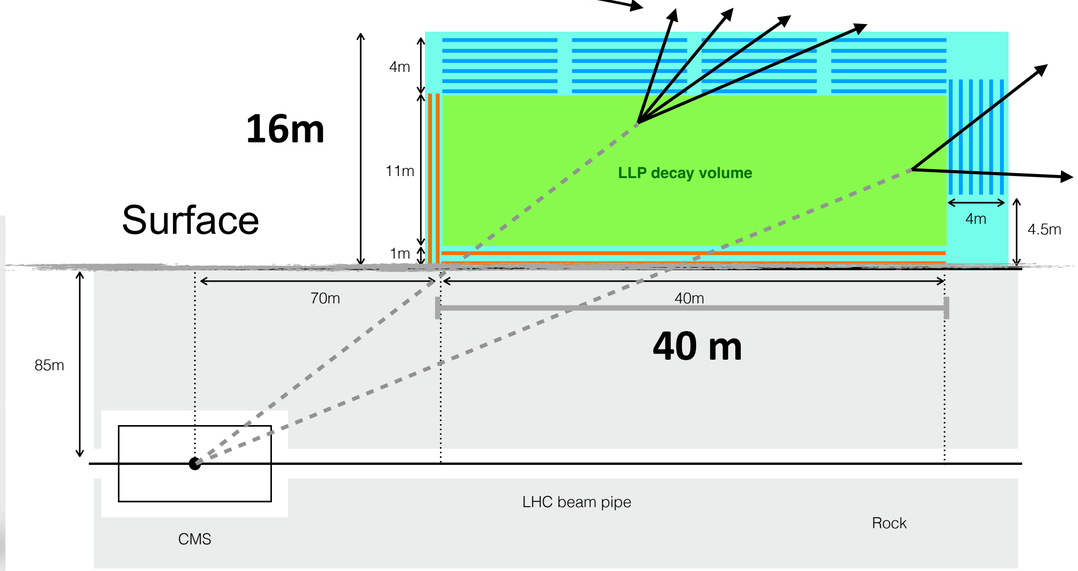
- Objective: **ultra long-lived particles**
- To be built on the surface over CMS during HL-LHC
- O(100m) rock shields against collision background
  - Test Stand demonstrator in 2018 confirmed background hypothesis
- Main Physics case: **high mass** ( 10 GeV - TeV) **hadronic LLP** decays
- Secondary Physics case: low mass (~GeV) low multiplicity LLP decays




6 scintillator tracking layers per module

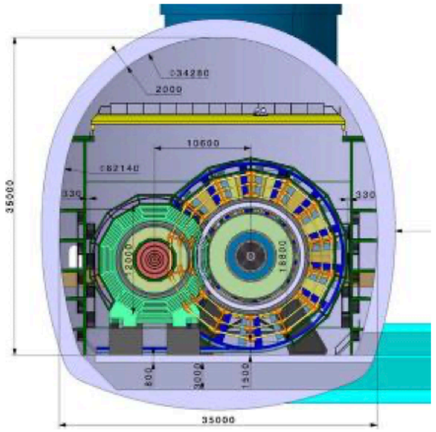



(100 x 100 x 25) —> (40 x 40 x 16) for cost reasons

# Dedicated experiments in future colliders

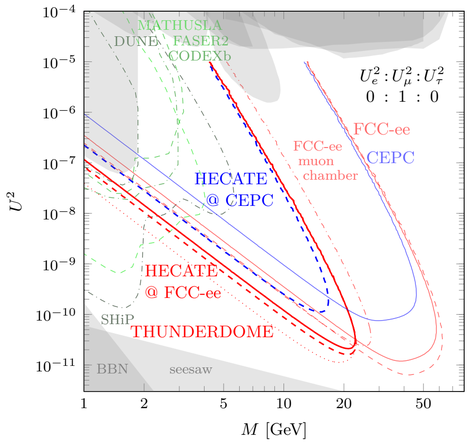
- Detectors for future colliders considering LLPs as a physics case for their design

- **Lepton collider ideas:**
- HECATE: Instrument cavern walls with scintillators
  - Phase space with no access in cosmology



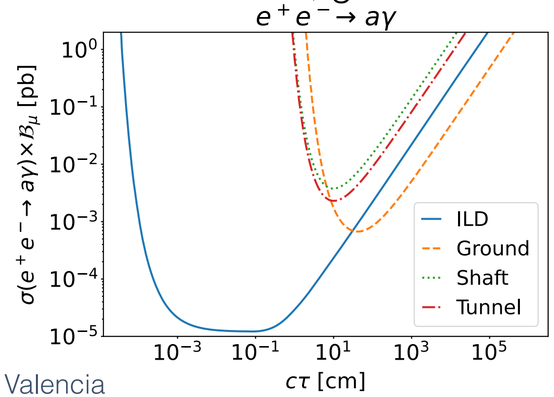
EPJC 81 (2021) 546

Heavy Neutral Leptons @ FCC-ee

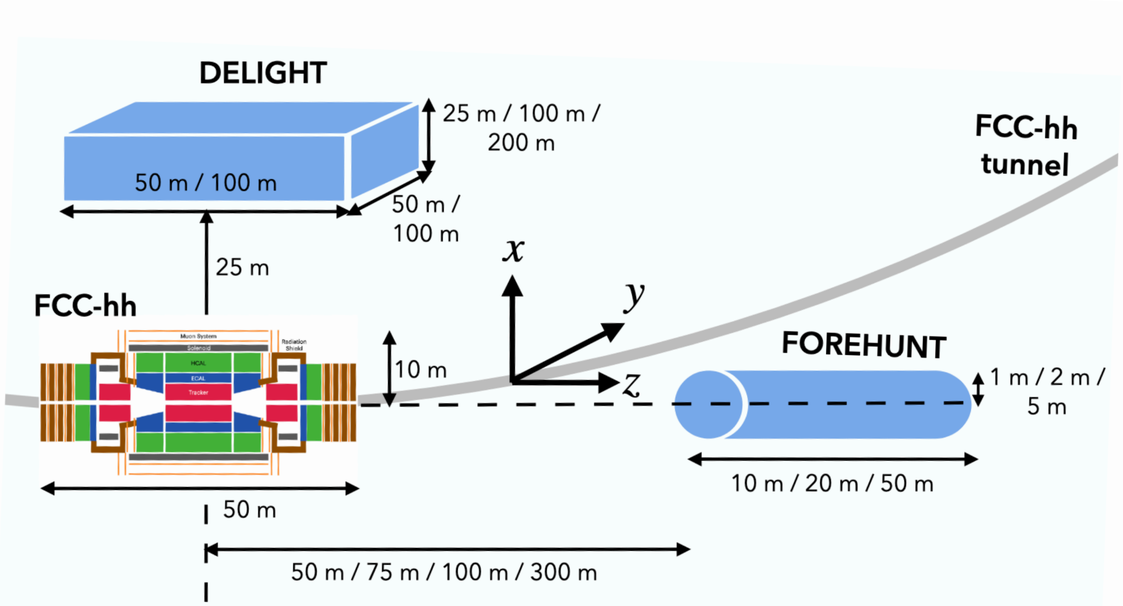



- Study at ILC: ILD + far detectors, good sensitivity for LL ALPs

PRD 107 (2023) 076022




- **Hadron collider ideas:**
- DELIGHT transverse detector (PhysRevD.106.095018)
  - MATHUSLA - like concept
- FOREHUNT forward detector (2306.11803)



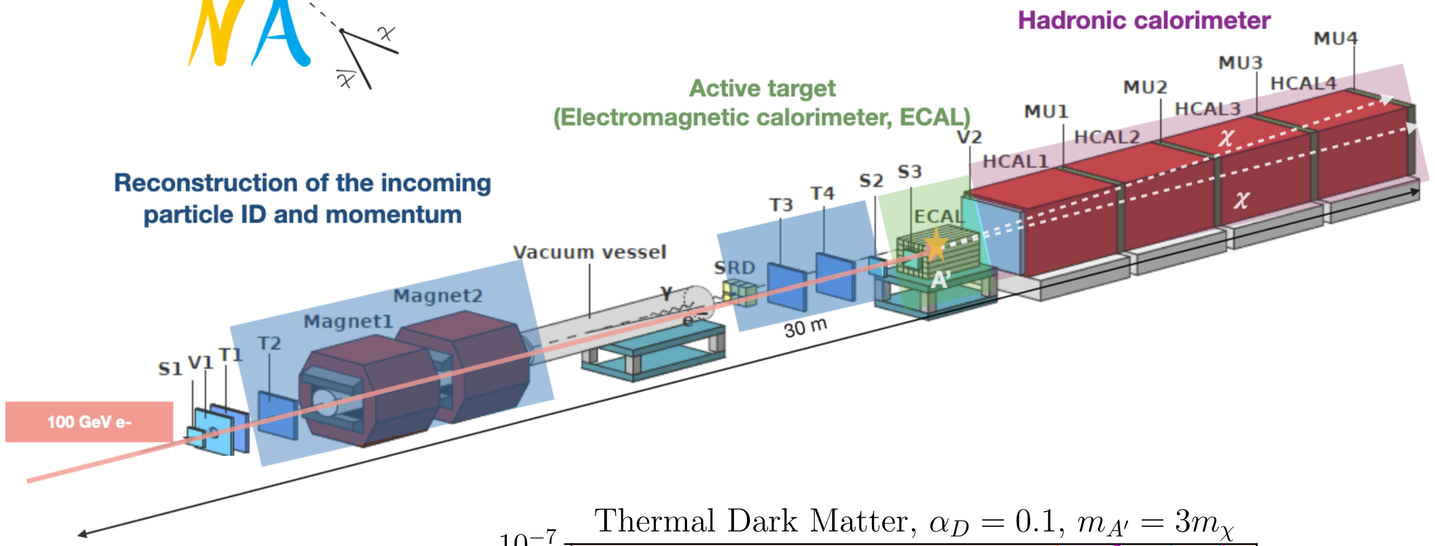
# LLPs beyond colliders

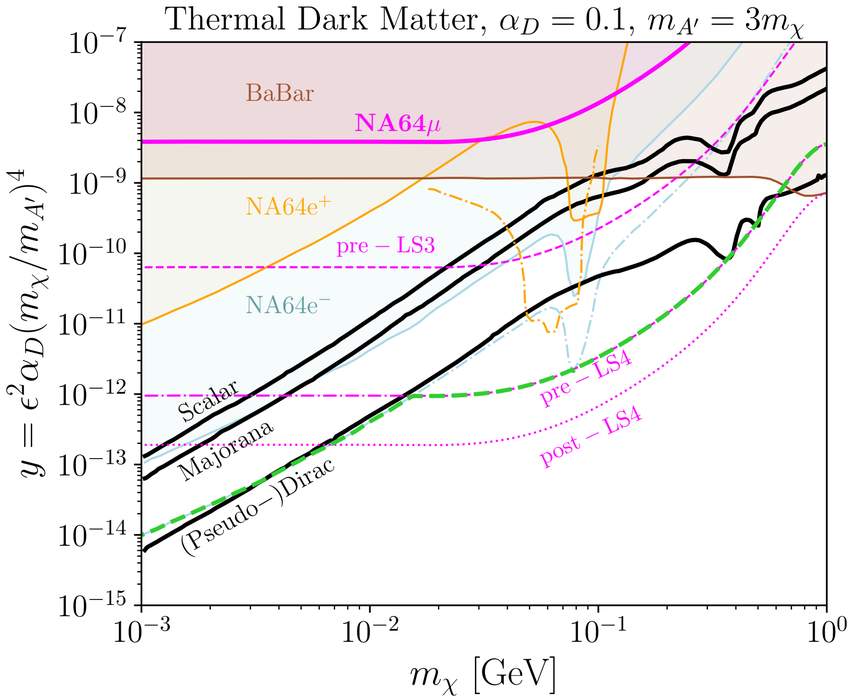
# LLPs beyond colliders

## NA64

- Objective: **light dark matter**
- North Area, fixed target using SPS electrons (and muons and hadrons) beams
- Hermetic detector: can measure MET
- Constraints set on ALPs, B-L Z' , inelastic DM

| Beam | Motivation | Pre-LS3 Statistics | Run 4 [particles on target] |
|---|---|---|---|
| *NA64e⁻* | *Leptophilic DS coupled to e⁻ LDM, inelastic DM, ALPs, scalar, Z', X17 …* | $3\times10^{12}$ ($2\times10^{12}$) | $10^{13}$ |
| *NA64e⁺* | *LDM (higher masses <0.25 GeV, several mediators axial, vector, pseudoescalar, scalar),…* | $10^{11}$ (a 70, 60, y test a 40 GeV) | **> $10^{11}$ for different energies** |
| *NA64μ* | *Leptophilic DS coupled to μ LDM (higher masses > 0.1 GeV, ALPs, Z', muon g-2, millicharge, μ→τ, …* | $3.5\times10^{11}$ | $2\times10^{13}$ |
| *NA64h* | *Hadrophilic DS Invisible decays of η, η', $K_0$* | Addenda of a dedicated program under preparation | |

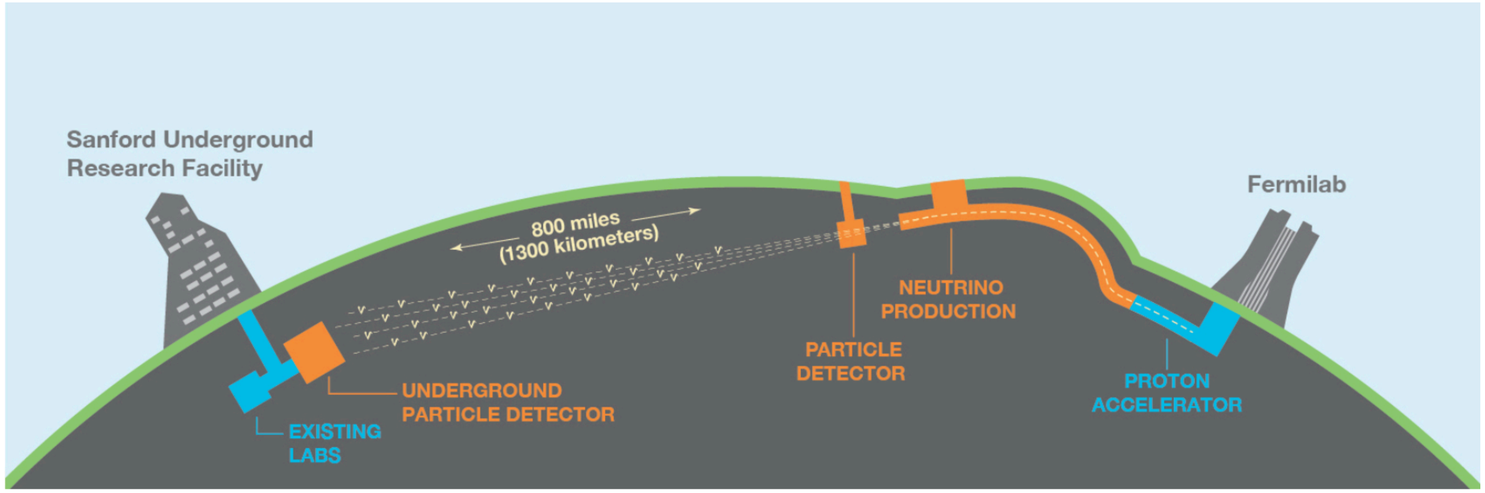


# LLPs beyond colliders

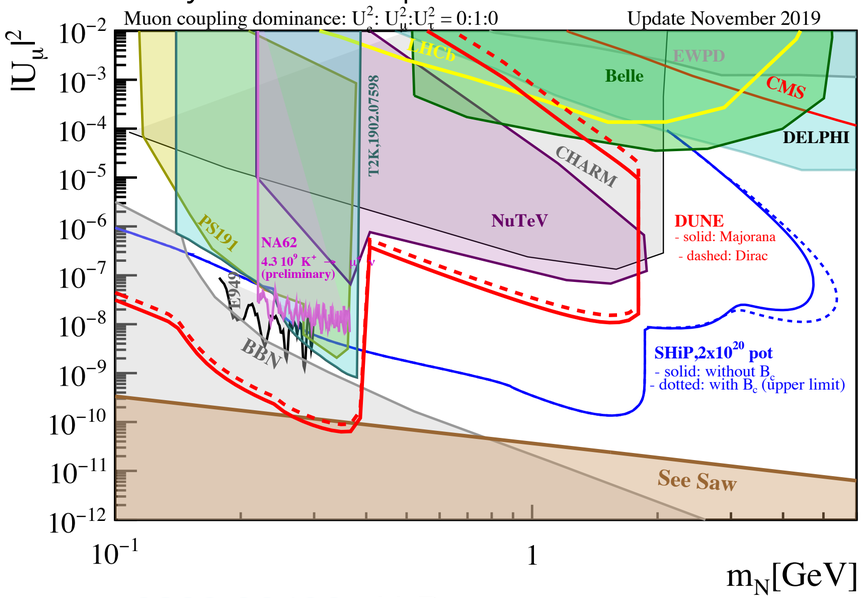
## DUNE

- LNBF source can produce charmed mesons in the beam
- DUNE ND can be used to search for long-lived HNLs, hidden sectors, SUSY, etc.
  - Would probe the lighter particles of the hidden sector: complementary to LHC heavier-mass searches

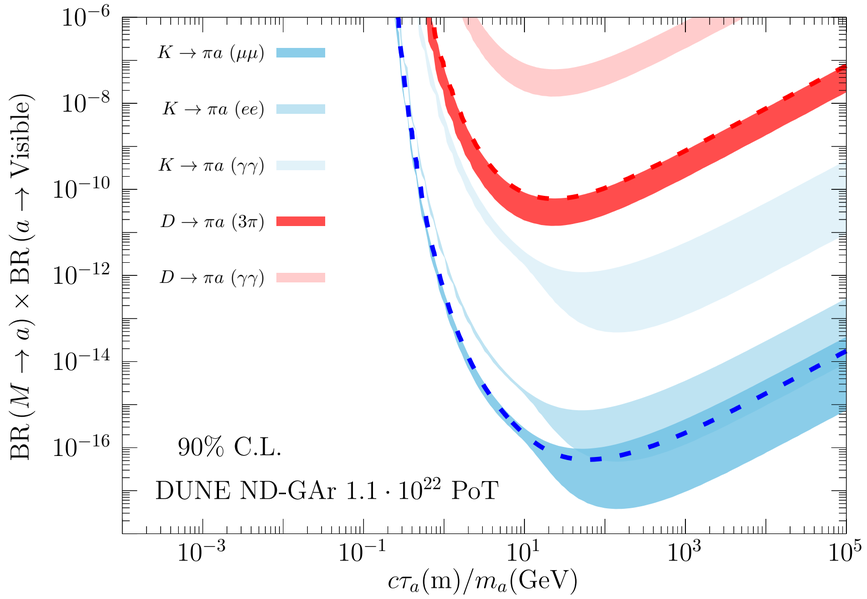



DUNE ND CDR:

Heavy Neutral Leptons



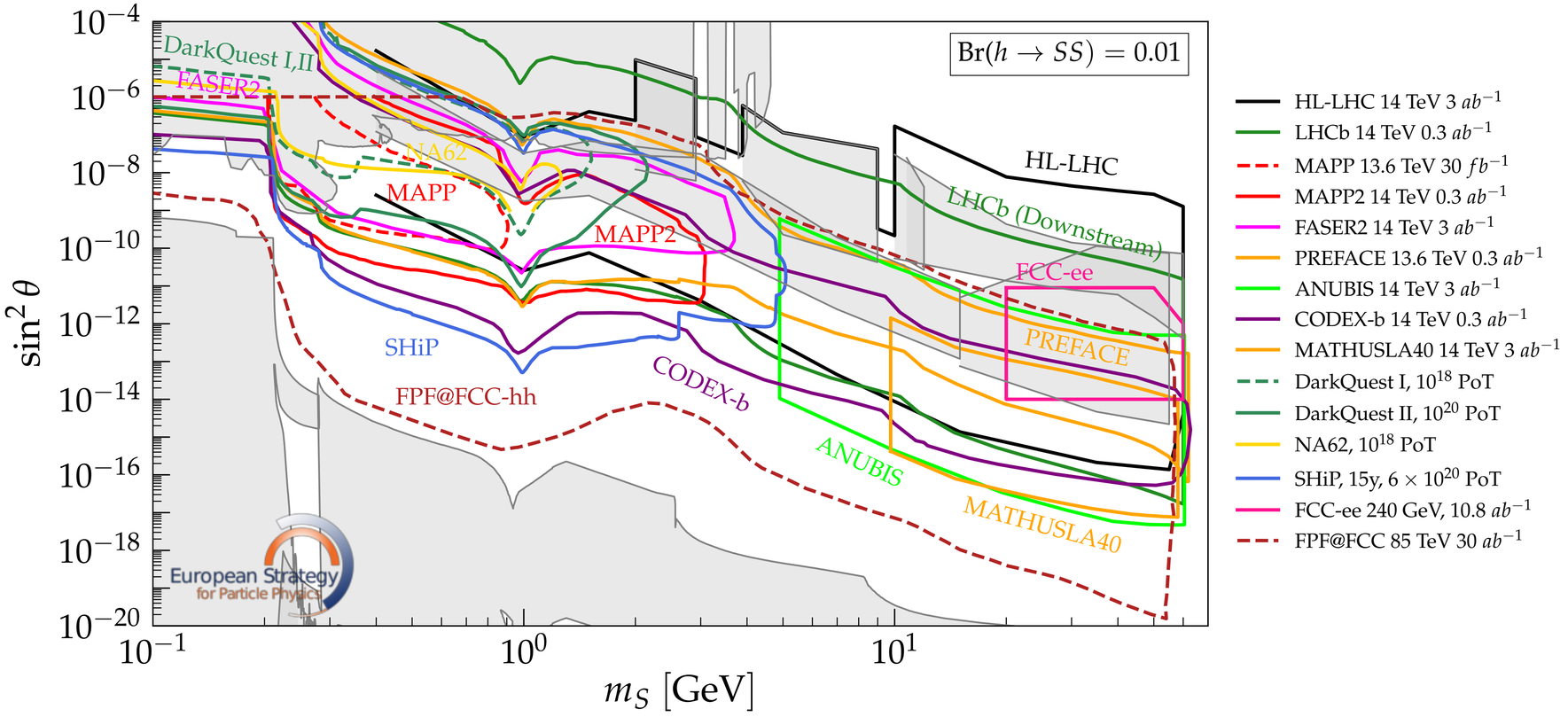

2309.06492: ALPs



# Complementarity is key

ESPPU 2025 Physics Briefing Book

## Higgs decays to scalars

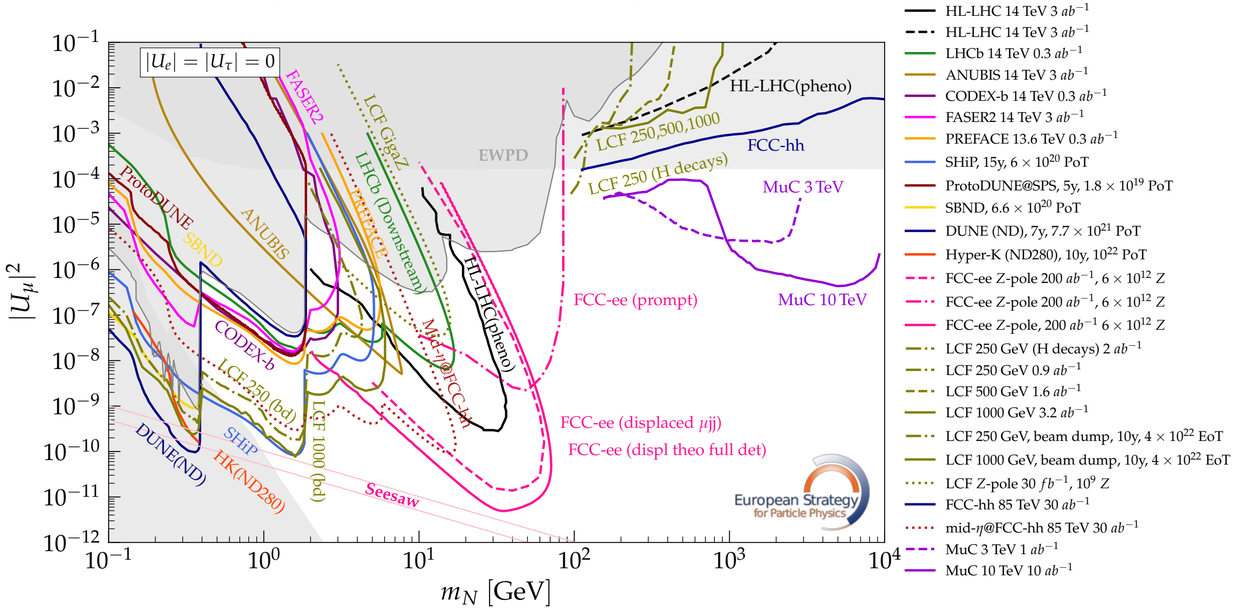



- Strong Spanish contribution in detectors:
- High mass region dominated by HL-LHC detectors
  - LHCb Downstream
  - CODEX-b
  - MATHUSLA
- Lower mass region mostly forward detectors
  - CODEX-b still competent

# Complementarity is key

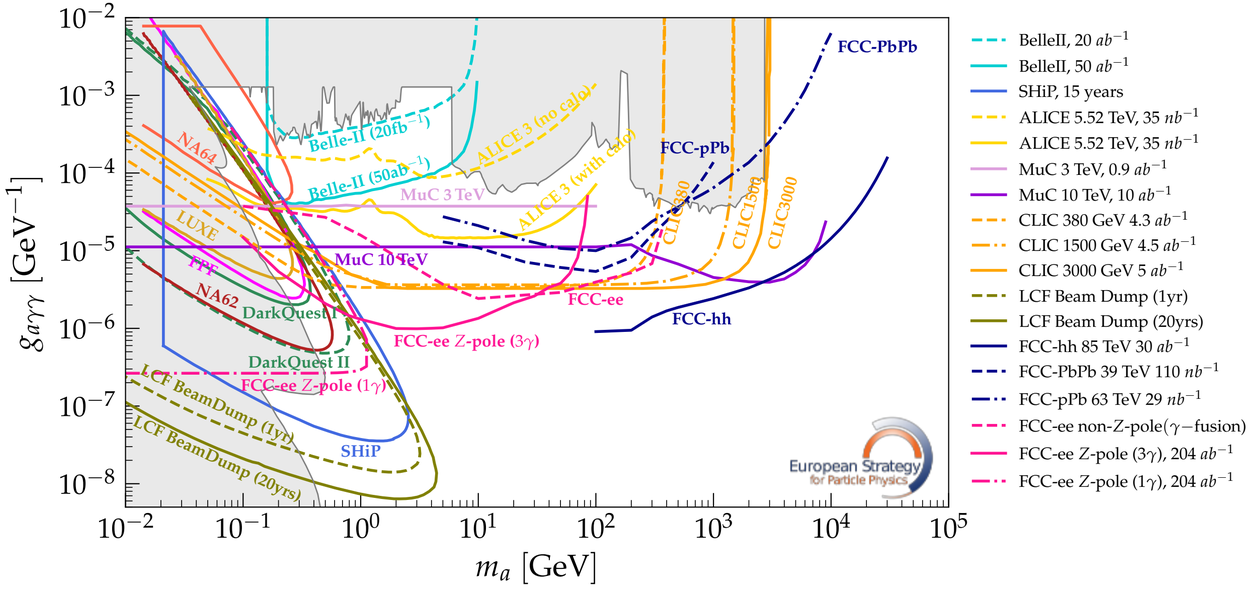
ESPPU 2025 Physics Briefing Book

## Heavy Neutral Leptons




- Strong Spanish contribution in detectors:
  - LHCb Downstream
  - CODEX-b
  - ProtoDUNE, DUNE (ND)

## ALP coupling to photons




- Strong Spanish contribution in detectors:
  - Belle II
  - NA64

# Are we missing anything we could be covering?

- The HL-LHC is around the corner
- Time to think about the goals for the end of the LHC era
  - Are there final states we risk missing because of lack of good **triggers**? Plan now, not lose an irrecoverable discovery!!
  - Are we using all the Run 4 **upgrade** potential for LLPs?
- What **theory** models / phase spaces are we not covering?
- Could **Anomaly Detection** be more broadly used for LLPs?
- **Reinterpretation**: is the communication experiments - theory community good enough? **@ Alberto Escalante, Weds 18:40**

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

CMS

# Summary

- Long-Lived Particles could be key in the discovery of new physics
- The interest in this topic is constantly increasing, for the LHC and beyond
- Great opportunities in the near future in colliders and beyond
- **Spanish community is in a very good position, leading major efforts**
- 15º LLP community workshop in Valencia
  - 100 attendants, 40% Spanish institutions, 27 nationalities
- Need to keep the leadership in this area!