Searches for Very Long-Lived Particles at the LHC

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Interplay between Particle and Astroparticle physics

Vienna, 09 September 2022

UNIVERSITY of WASHINGTON

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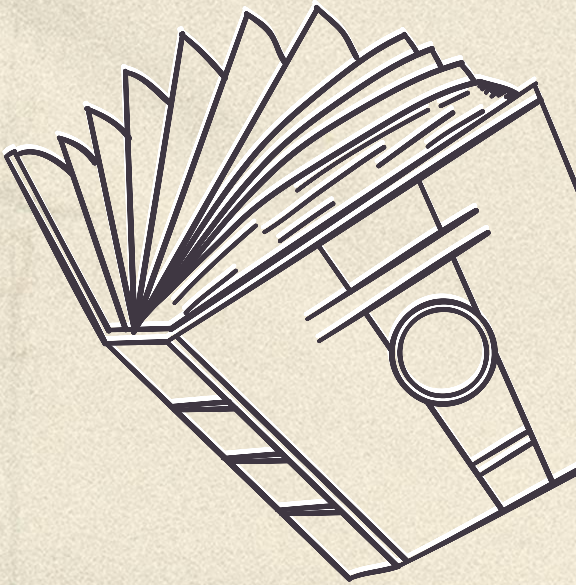
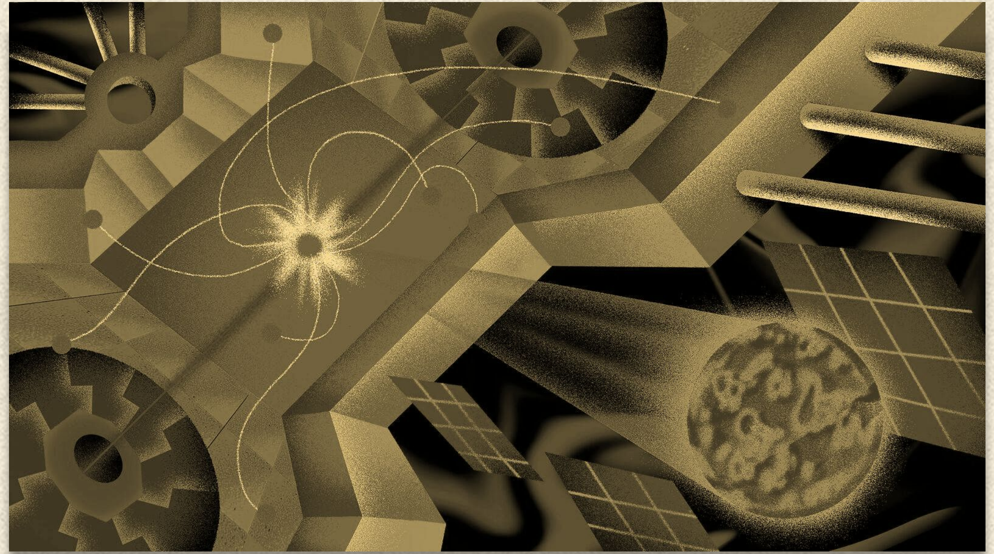




01 Motivations

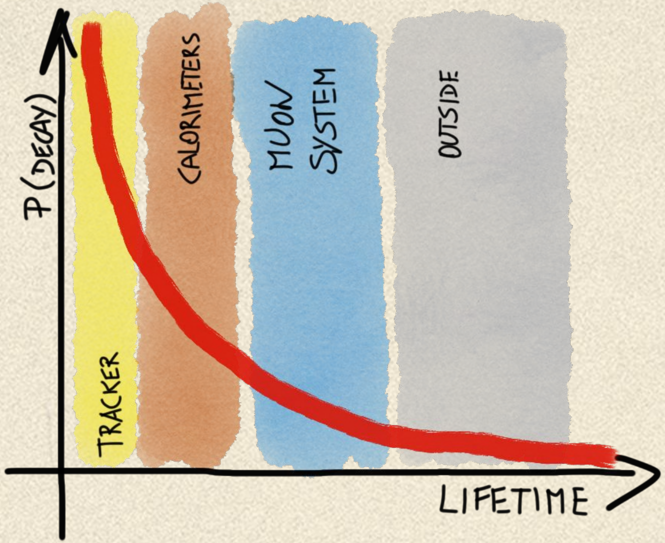
Theory intro in Susanne's talk today
LLPs in current LHC experiments in Daniele's talk on Wednesday

Long-Lived Particles Lifetime

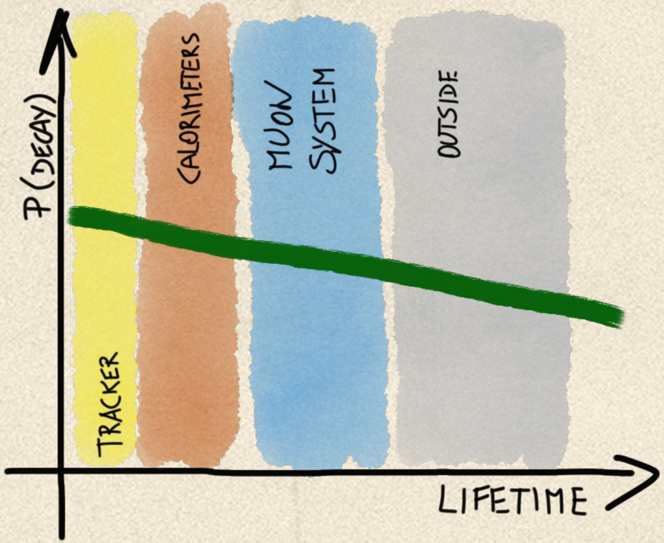
The particle lifetime is a free parameter in the model

- It is sampled from an exponential
- **Detector signature strongly depend on boost/mass of the LLP**

Need to adapt the search strategy!



Most of the decays happen **inside** the detector

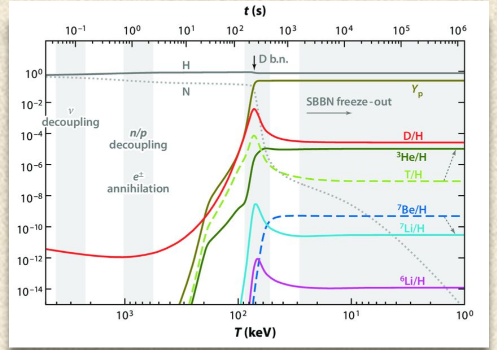


Most of the decays happen **outside** the detector

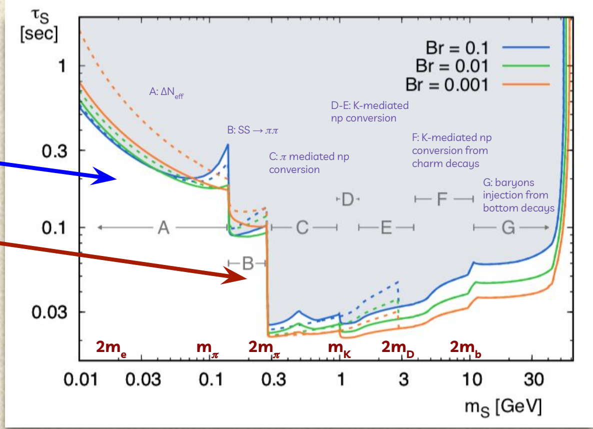
LLP Lifetime: Any Limit?

arXiv:1706.01920

The lifetime of a metastable particle can be limited by cosmology, in particular by the Big Bang Nucleosynthesis (BBN)



- **BBN very well understood within the SM physics and well constrained**
  - Happened between ~10 s - 15 mins after the Big Bang
- LLP lifetime should be smaller or n/p ratio should have been increased by mesonic and nucleonic LLP decays spoiling the final light nuclei abundances
- Possible constraint studied on a scalar model coupled through Higgs portal (h→ss)
  - For $m_s < 2m_\mu$ → lifetime can go up to 1 s
  - For $2m_\mu < m_s < m_h/2$ → lifetime < 0.1 s
- Conclusions do not depend strongly on BR(h → ss)



LLP Geometrical Acceptance

What shapes the sensitivity versus lifetime?

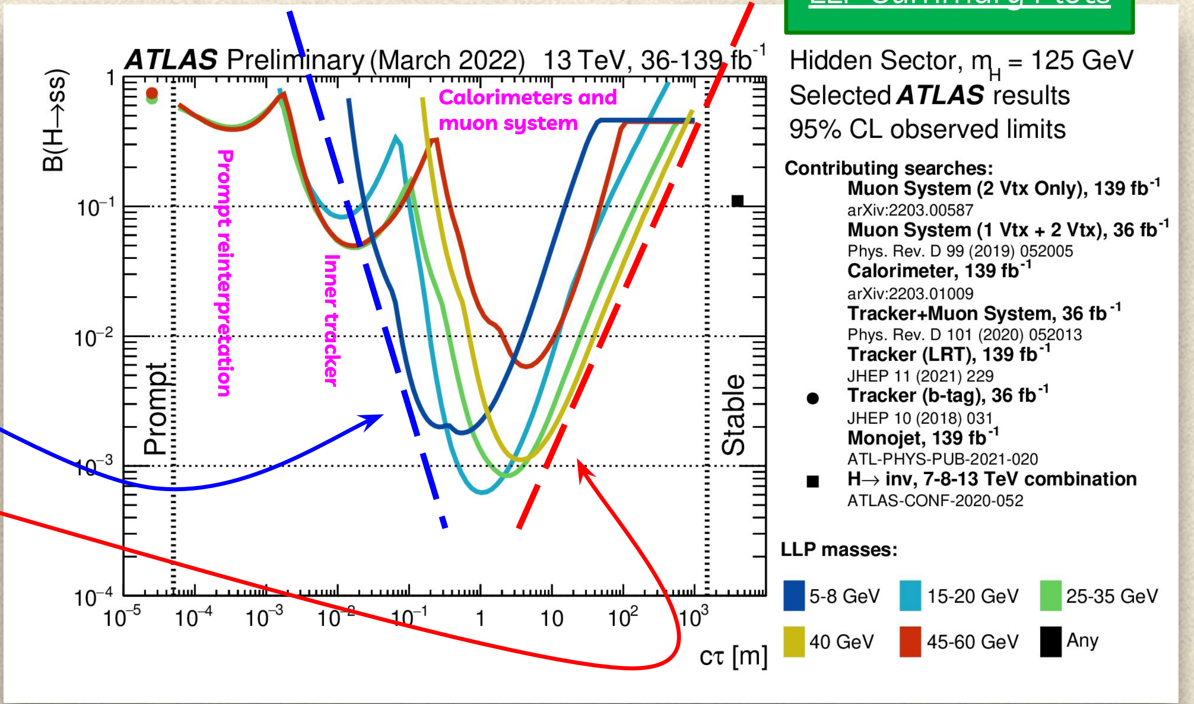
$$P = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{L_1}^{L_2} dL\, \frac{1}{d} e^{-\frac{L}{d}}$$

$$\approx \frac{\Delta\Omega}{4\pi}\, e^{-\frac{L_1}{d}}\, \frac{L_2 - L_1}{d}$$

$L_2 - L_1$ = detector length

d = average LLP decay length

LLP Summary Plots



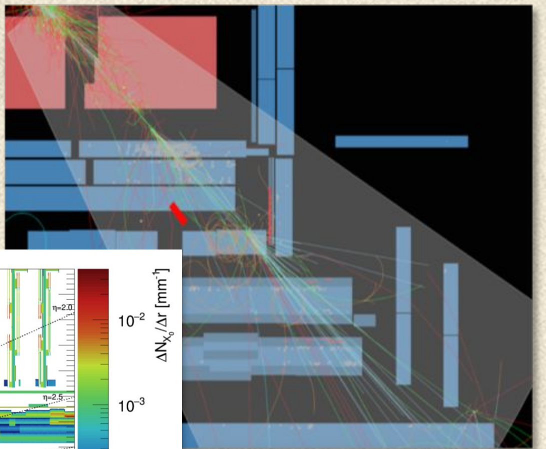
- Good solid angle coverage → lifetime independent
- Sensitivity to smaller lifetimes → need high efficiency close to the IP
- Sensitivity to larger lifetimes → need longer detector

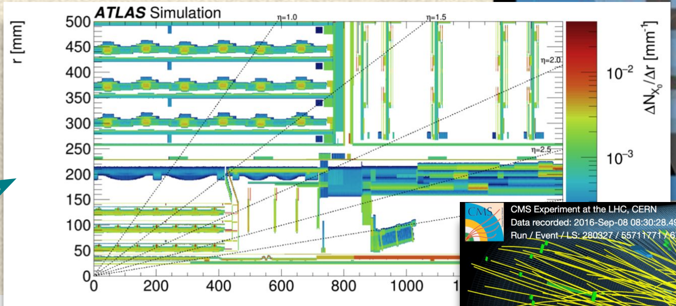
LLP Challenges @ Colliders

LHC detectors are optimised to detect prompt SM particles

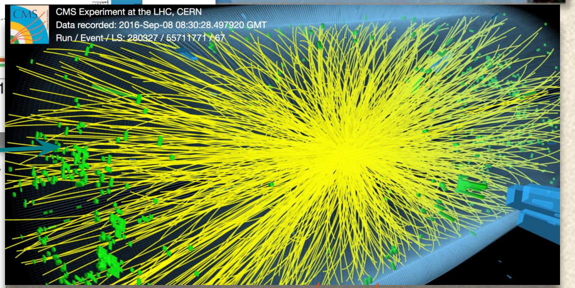
- BSM particles can produce final states that might be very difficult to study due to complicated backgrounds
  - Instrumental backgrounds
  - Large QCD jet production
  - Material interaction
  - Pile-up problems
  - Beam induced background

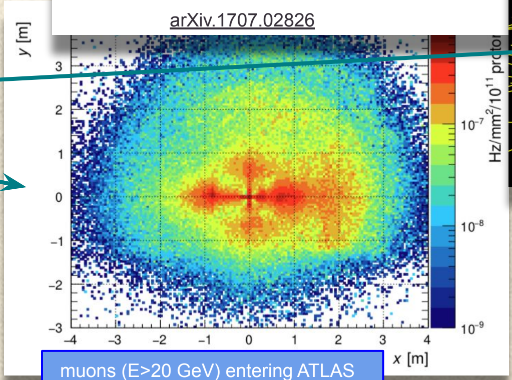
- Need to develop
  - **Dedicated triggers**
  - **Custom reconstruction objects**
  - **Very robust background modelling and rejection**



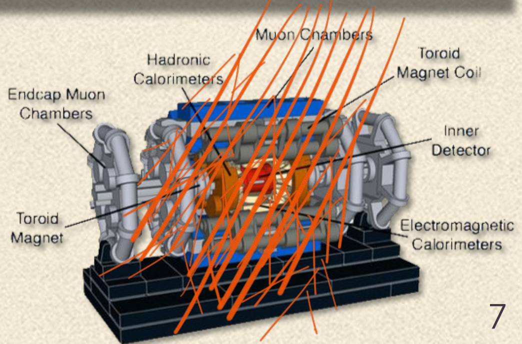


arXiv.1707.02826



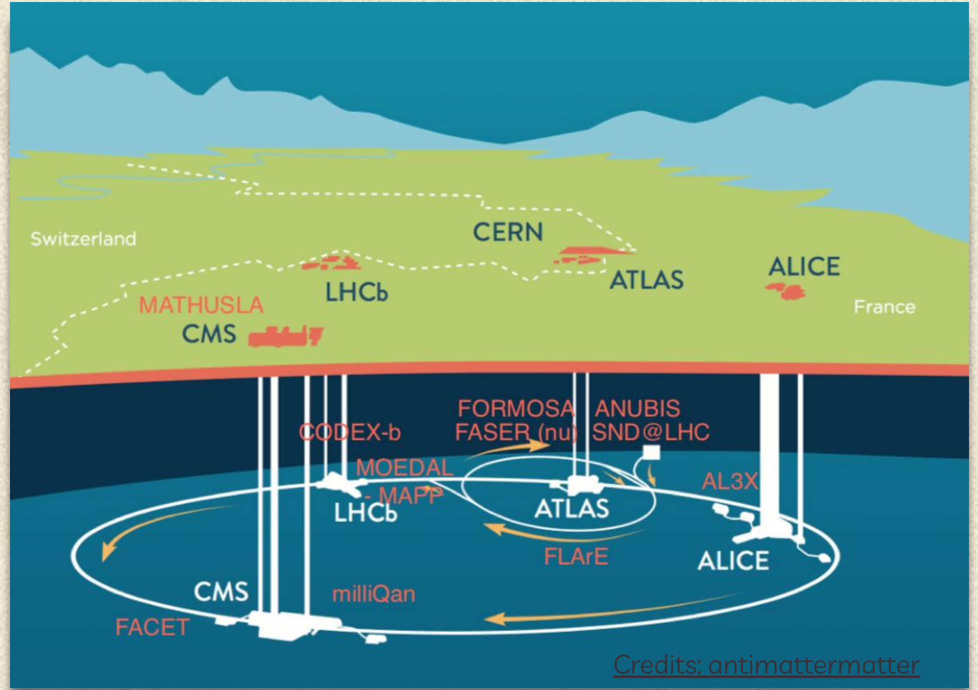


muons (E>20 GeV) entering ATLAS at z=22.6 m [arXiv:1810.04450]

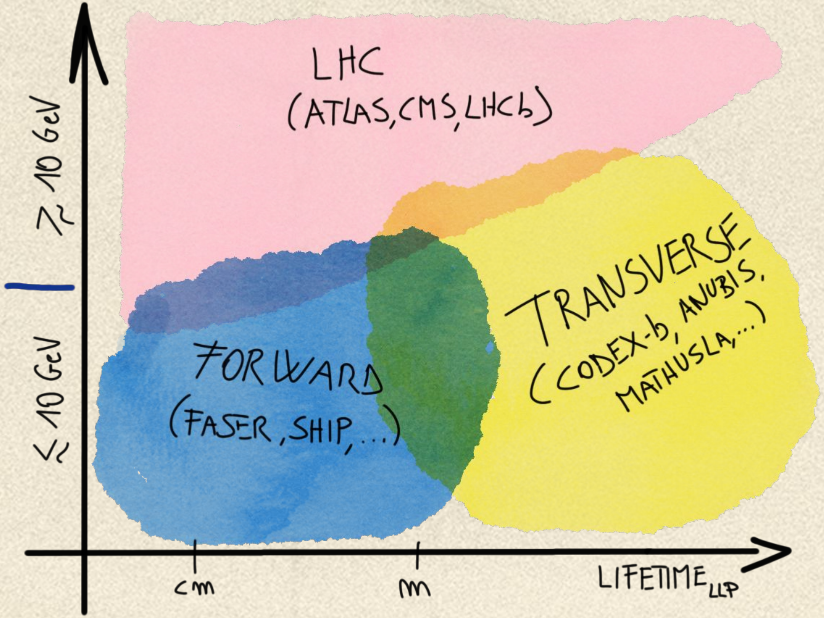


The Proposed LLP Detectors @ LHC

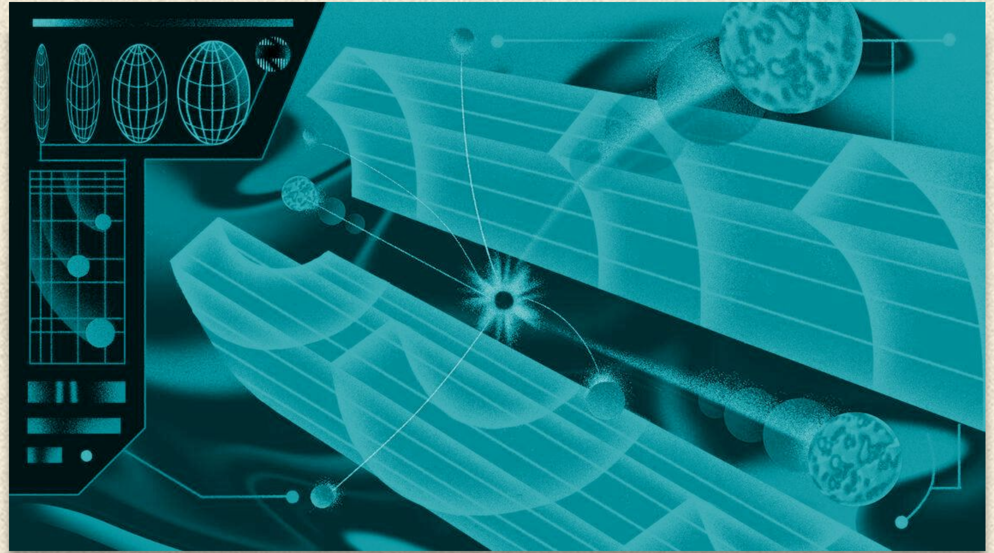
Big variety of complementary detectors



Credits: antimattermatter matters



- Allow to cover a big range of lifetimes up to BBN limit, couplings, masses, decay modes



02

Transverse Neutral LLP detectors

MATHUSLA

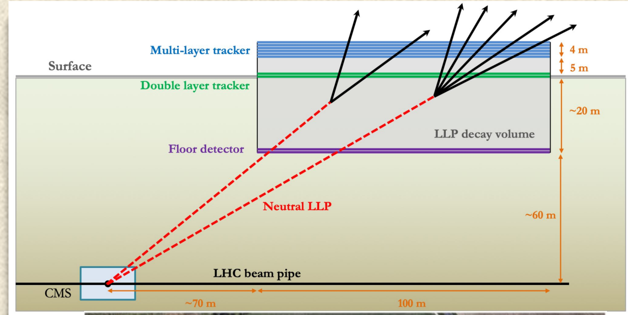
[arXiv:2005.02018](#) (Test stand)
[arXiv:2009.01693](#) (update LoI)
[arXiv:2203.08126](#) (Snowmass22)

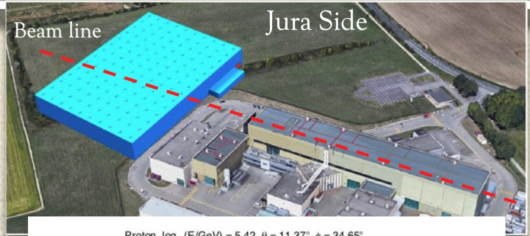
Dedicated detector sensitive to neutral LLP with lifetime up to BBN

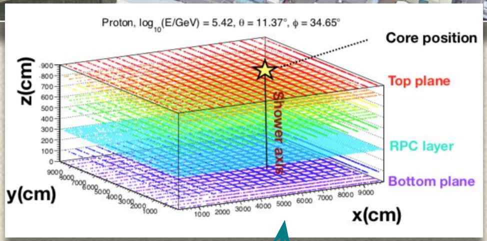
- Proposed a **large area surface detector located above CMS**
  - **Robust tracking** + **excellent background rejection**
  - Floor detectors to reject interactions occurring near the surface
  - **Extruded scintillators + SiPMs** (good time/space resolution)

- **Cosmic** μ rate of about **1.7 MHz** and **10 Hz LHC** μ rejected with timing
- **LHC neutrinos:** expected 0.1 events from high-E neutrinos (W, Z, top, b), ~1 events from low-E neutrinos (π/K**)** over the entire HL-LHC run

- **Upward atmospheric neutrinos** (**70 evts/y above 300 MeV**) "decaying" to low momentum proton





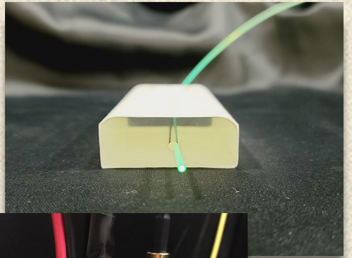


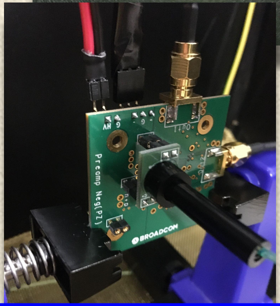
- **Advantages**: sensitive to **very long lifetimes**, almost **fully shielded from IP background**, can do **interesting cosmic ray studies**
- **Drawback**: big detector, need to excavate 20 m (which increases the cost)

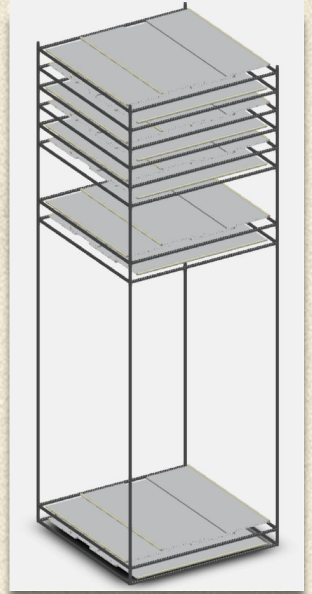
MATHUSLA - Status

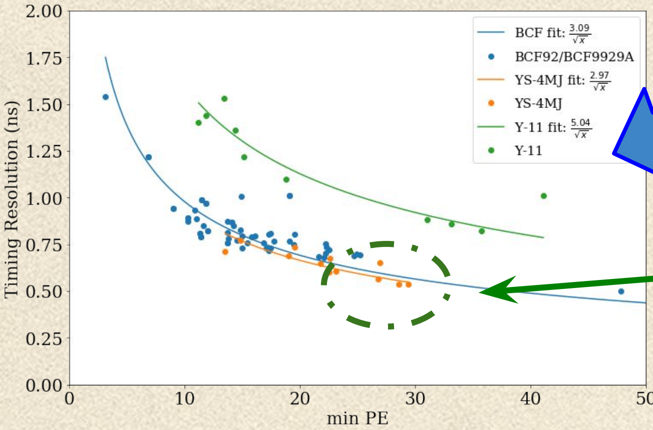
Extruded scintillator bars with wavelength shifting fibers coupled to SiPM (tested extrusion facilities - Fermilab and Uniplast)

- **Critical features** of the detector design
  - Separates downwards from upwards going tracks
  - Reject low beta particles from neutrino QIS
  - **→ Need ~1 ns with >15 photoelectrons**









Timing measurement for a 5 m long fiber through a 1 x 4 cm^2 extrusion located at the center of the fiber

Timing resolution of ~0.54 ns (i.e. 9 cm RMS position resolution) well within MATHUSLA requirement. **Worst case light-yield was 29 PE**

- **Finalising first design of detector layout, DAQ and trigger**
- **Conceptual Design Report** to be published soon

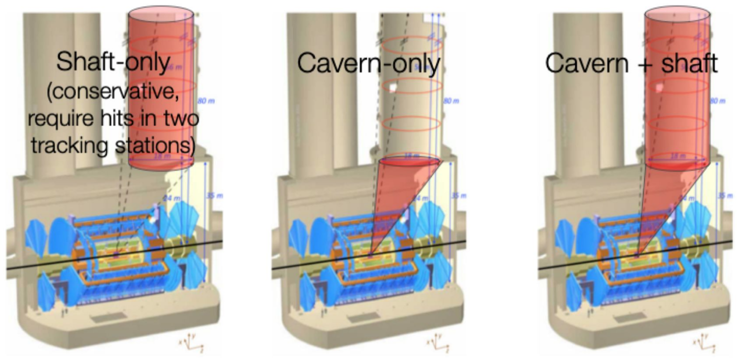
ANUBIS

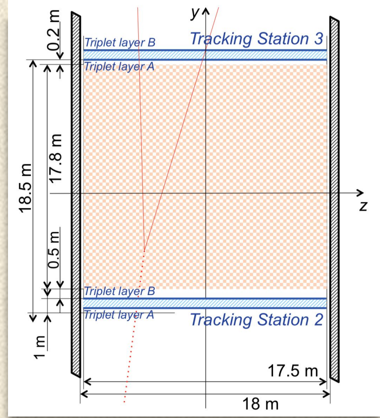
arXiv:1909.13022 (proposal)

Conceptually similar to MATHUSLA

AN Underground **B**elayed **I**n-**S**haft: i.e. instrumenting the ATLAS shaft with tracking detector for HL-LHC

- **4 stations of RPCs for tracking** (2 triplet each)
- Timing to reject cosmic rays
- Can be combined with ATLAS information as veto and background estimation
- Assuming background similar to the LLP searches in ATLAS muon system (**need 4-50 events for evidence)**





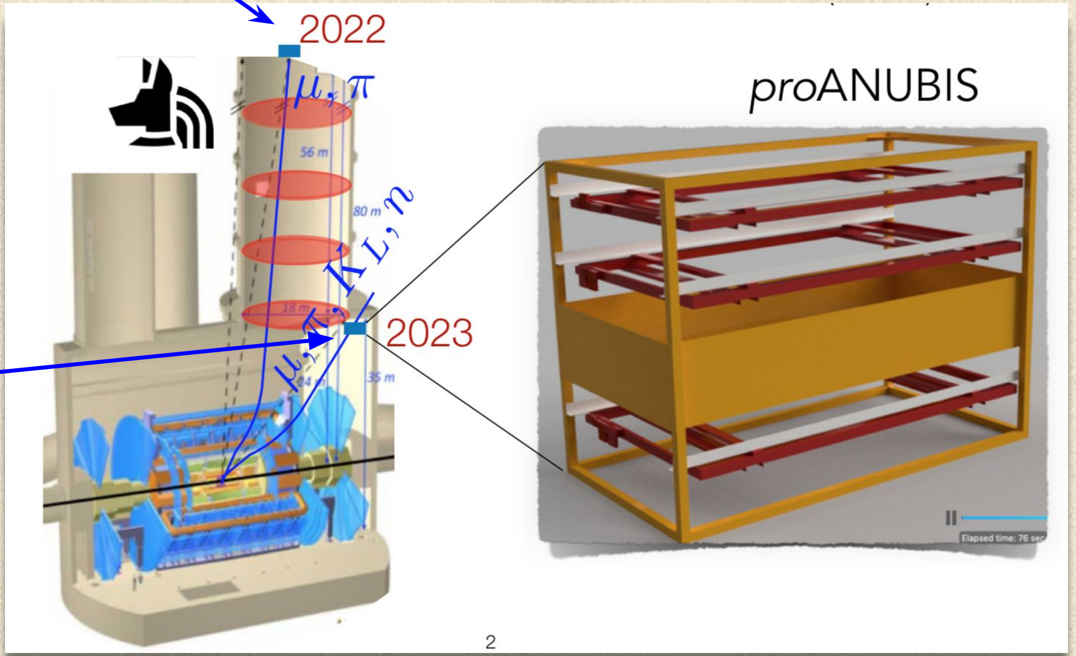
- **Advantages**
  - Solid angle comparable to MATHUSLA
  - Up to 10^3 better sensitivity wrt current/approved future experiments for neutral LLPs with $c\tau \gtrsim 10^2$ m
  - Moderate costs: $O(10)$ MCHF
- **Drawbacks**
  - Basically no shielding: need a very good understanding and modelling of background from the IP

ANUBIS – Status

More details in here and here (XI LLP workshop)

Currently building a 1.8 x 1 x 1 m^3 prototype to measure the flux and correlated to ATLAS during Run 3

- **2022 target**
  - Commissioning, study tracking performance, synchronisation with ATLAS
  - Rate of secondaries from hadrons interacting with concrete, probability to see hadrons from punch-through jets
- **2023 target**
  - Continue 2022 studies + measure rate of K_L, n in events with jets pointing towards proANUBIS
  - Validation of Geant4 simulation



- **Some sensitivity to NP?** I.e. charged massive particles with β ≈ 1 (not small enough to be seen by ATLAS)

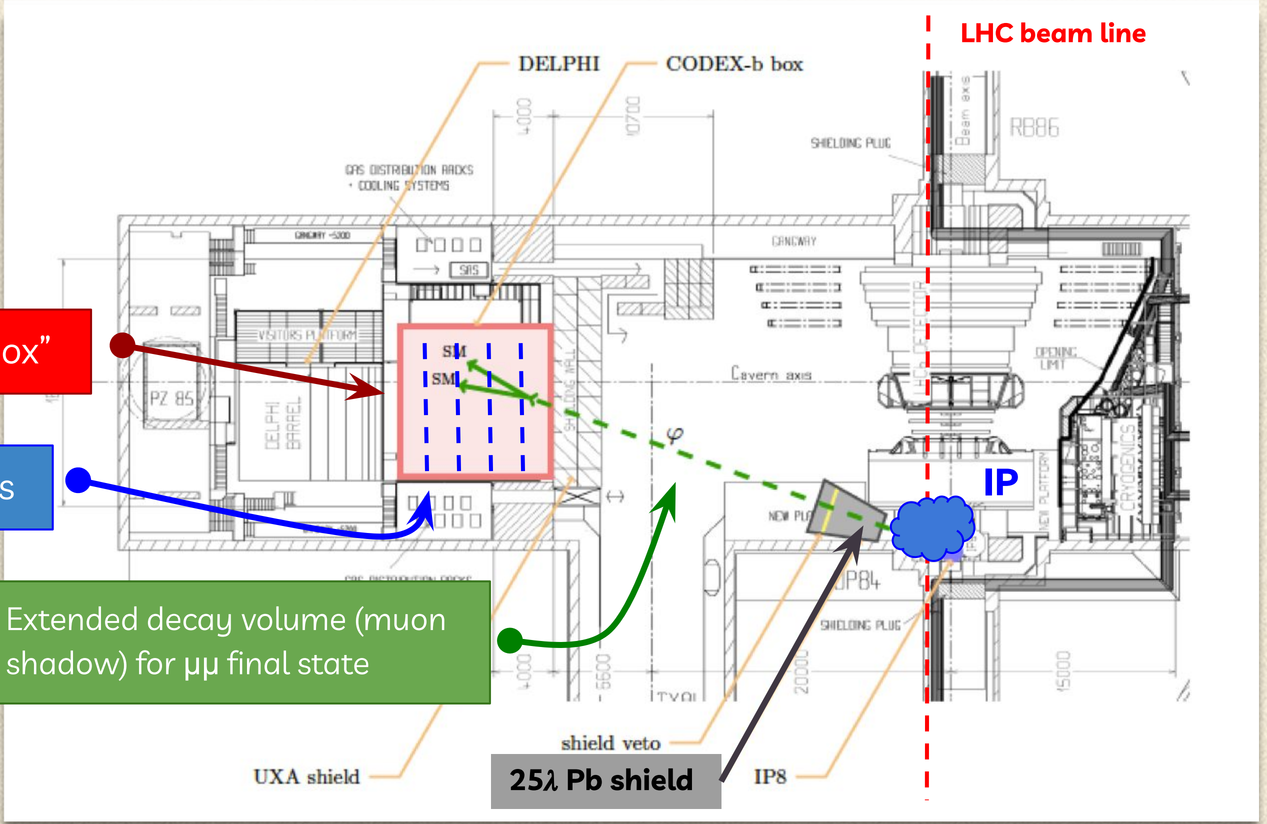
CODEX-b

arXiv:1911.00481 (proposal)
arXiv:2203.07316 (Snowmass22)

Conceptually similar to MATHUSLA

COmpact **D**etector for **EX**otics at LHC**b** (theoretically **well-motivated ≲O(10 GeV) LLP**)

- LHCb DAQ system moved to the surface during LS2
- **Free space behind a 3 m thick concrete radiation shield in UXA** cavern (~25m from IP)

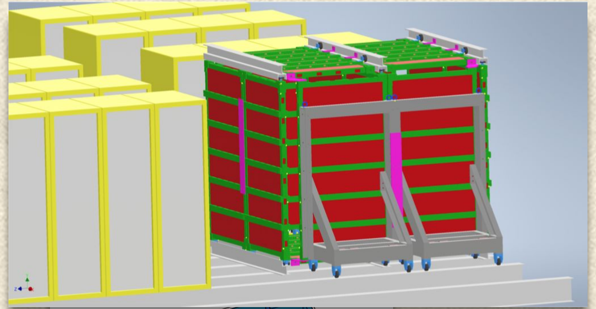


- **Advantages**: easy interface with LHCb
- **Disadvantages**: ~1/100 MATHUSLA sensitivity

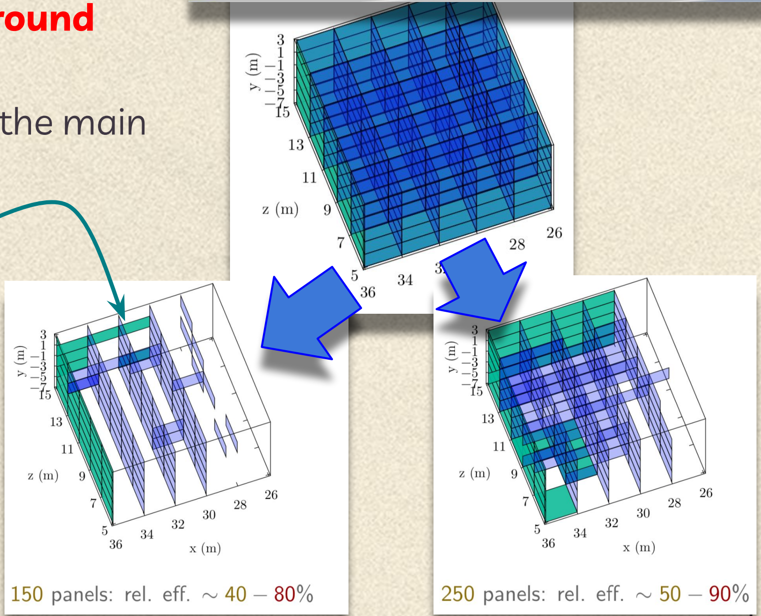
CODEX-b - Status

More details in this talk (XI LLP Workshop)

A small demonstrator detector 2 x 2 x 2 m^3 made or RPC triplets will be installed in the old LHCb HLT server room



- **Main goals**
  - Test **tracking technology** and **integration** with LHCb
  - Demonstrate the **ability to reconstruct SM background** inside the detector
  - Prove the mechanical structure and its scalability to the main detector
  - Optimise the detector shape and tracking layout
    - Considering also possible different geometry/orientation/position
- The **tracking layer surface area is the main driver of costs and installation time**
- **Module production should start by the end of this year**



AL3X

arXiv:1810.03636 (proposal)

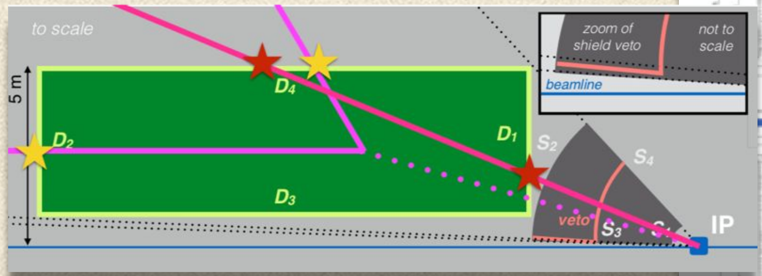
Conceptually similar to MATHUSLA

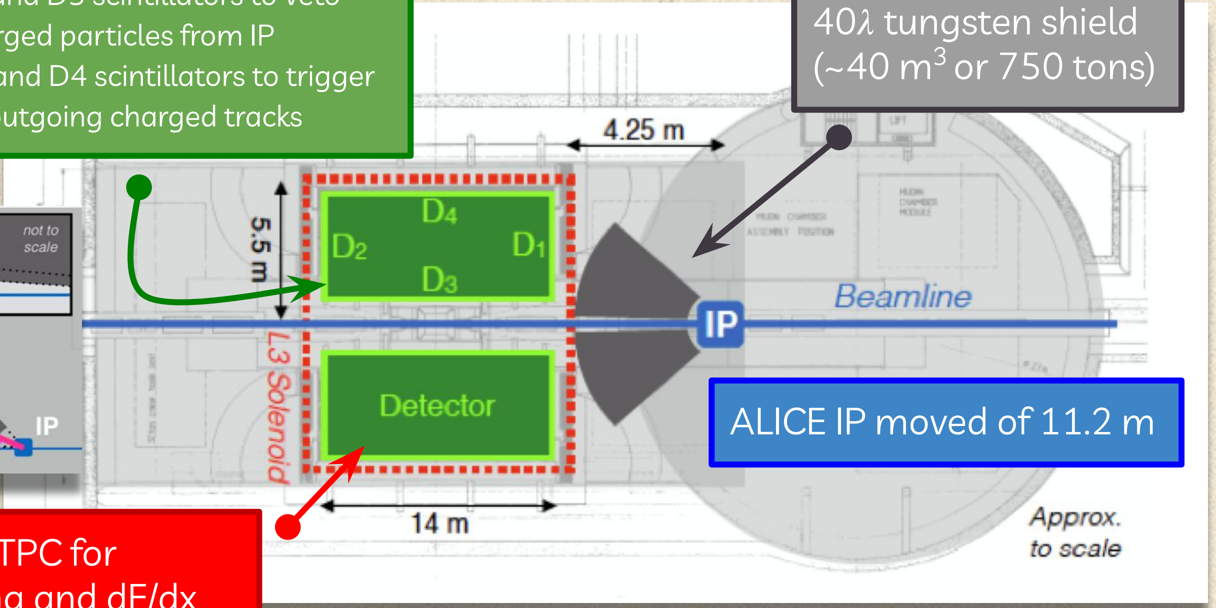
A Laboratory for **L**ong-**L**ived e**X**otics

- Reconfigure ALICE detector and its collision point at HL-LHC for dedicated LLP search
- 1/10 MATHUSLA sensitivity at long lifetimes, **MUCH BETTER at short lifetimes**
- Requires ≲ **(Eiffel Tower) worth of shielding,** **significant upgrades to beam optics**

D1 and D3 scintillators to veto charged particles from IP
D2 and D4 scintillators to trigger on outgoing charged tracks

40λ tungsten shield ($\sim$40 m^3 or 750 tons)





ALICE IP moved of 11.2 m

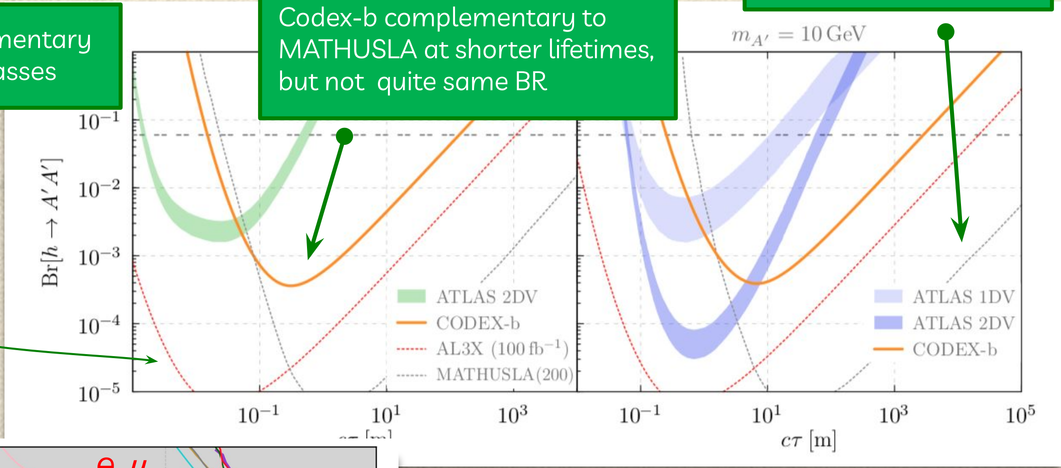
ALICE TPC for tracking and dE/dx

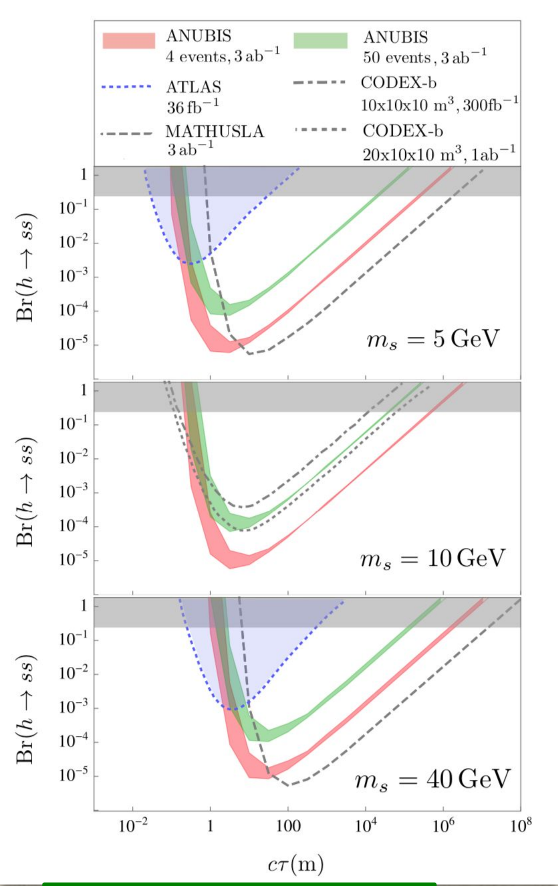
(Some) Sensitivities

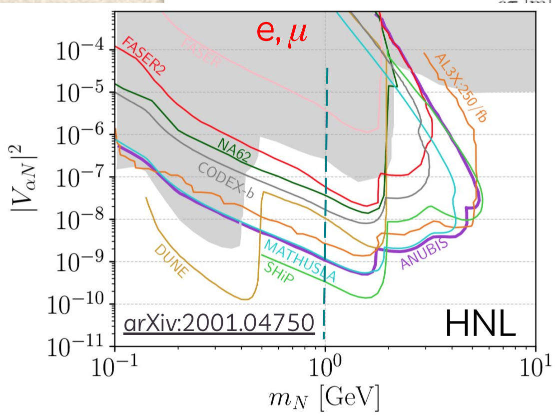
AL3X complementary for smaller masses

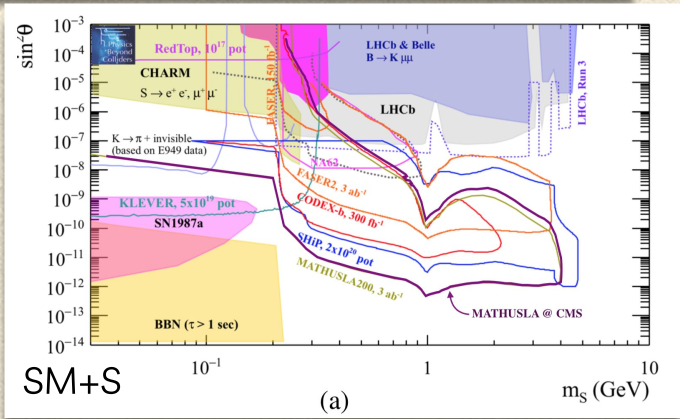
Codex-b complementary to MATHUSLA at shorter lifetimes, but not quite same BR

MATHUSLA has good sensitivity for masses >5 GeV and long LT

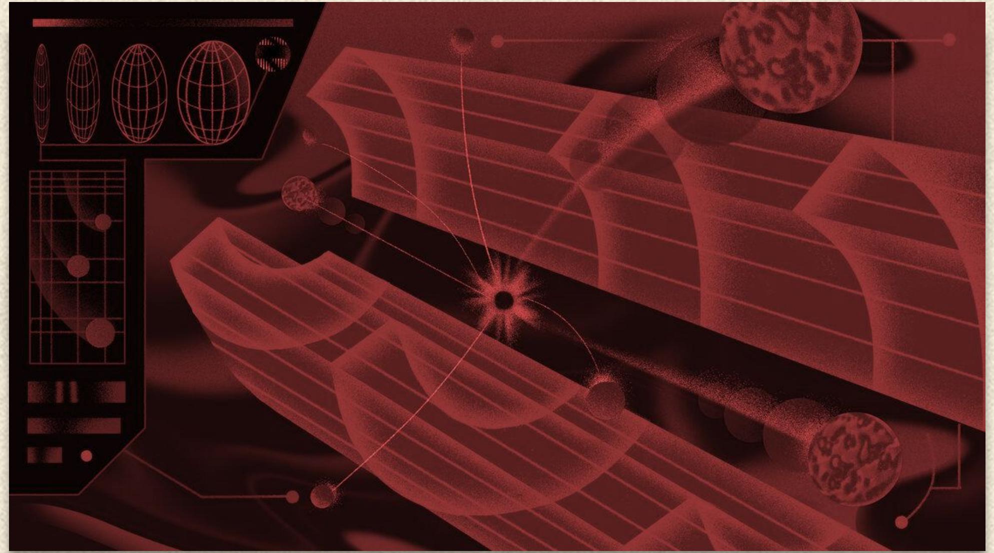








ANUBIS close to MATHUSLA in BR, shifted toward smaller LT (closer to IP)



03

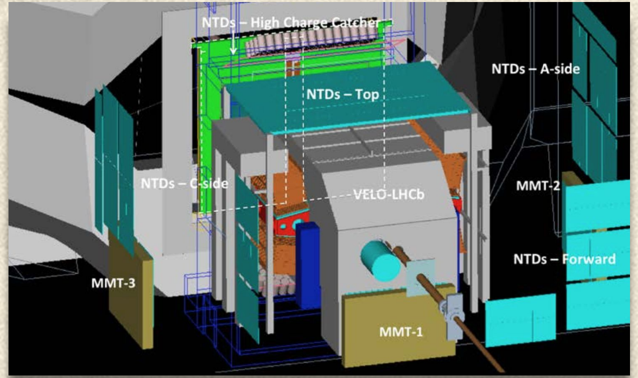
Transverse Charged LLP detectors

Moedal

Moedal (PhysRevLett.126.071801, PhysRevLett.123.021802)

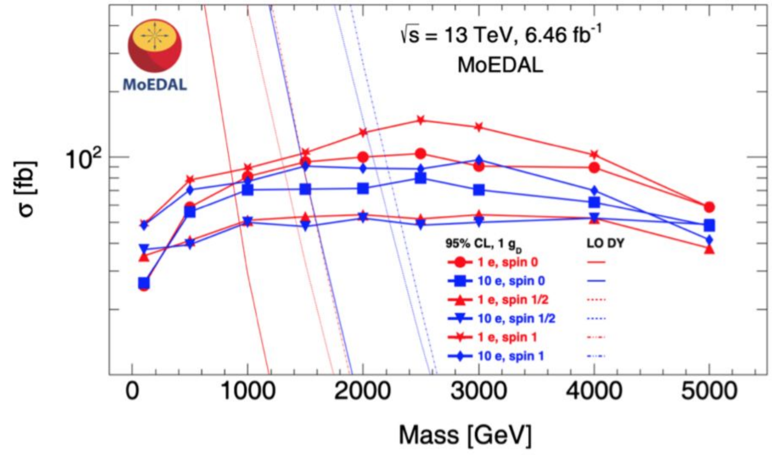
Experiment located in the LHCb cavern looking for highly ionizing particles, magnetic monopoles, pseudo-stable charged particles

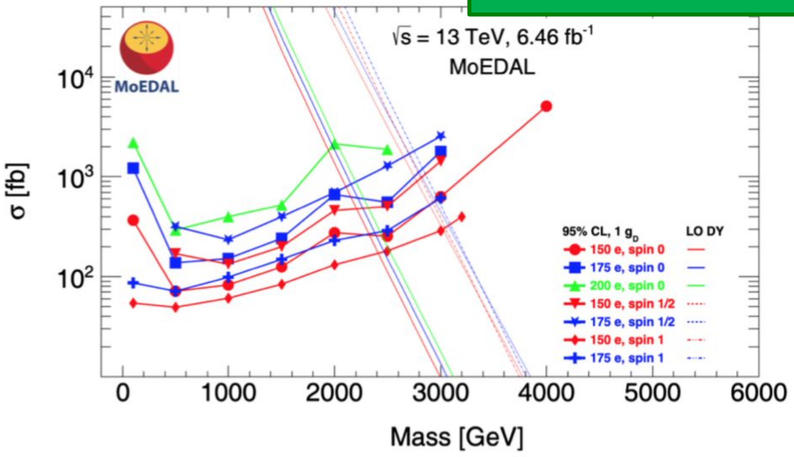
- It uses magnetic monopole traps and nuclear track detectors
- **Future plans**
  - **MAPP** (in Run 3) to detect millicharged particle (0.001 e)
  - **MALL to detect charged very LLP**



Forward region

First search for Dyons!

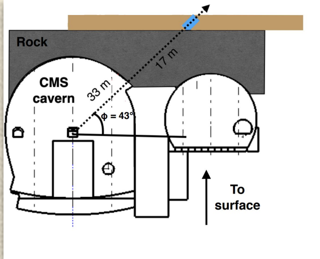




Milliqan

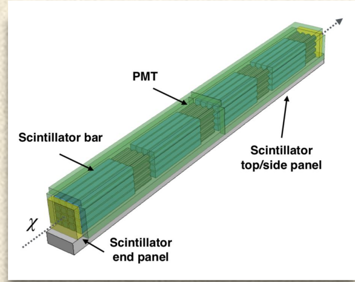
Milliqan (LoI, arXiv:1607.04669, Run 3 updates arXiv:2104.07151)

Experiment to detect “milli-charged” particles (0.3-0.001e) with O(GeV) masses produced by pp collisions at CMS

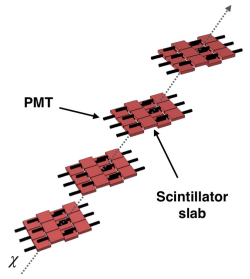


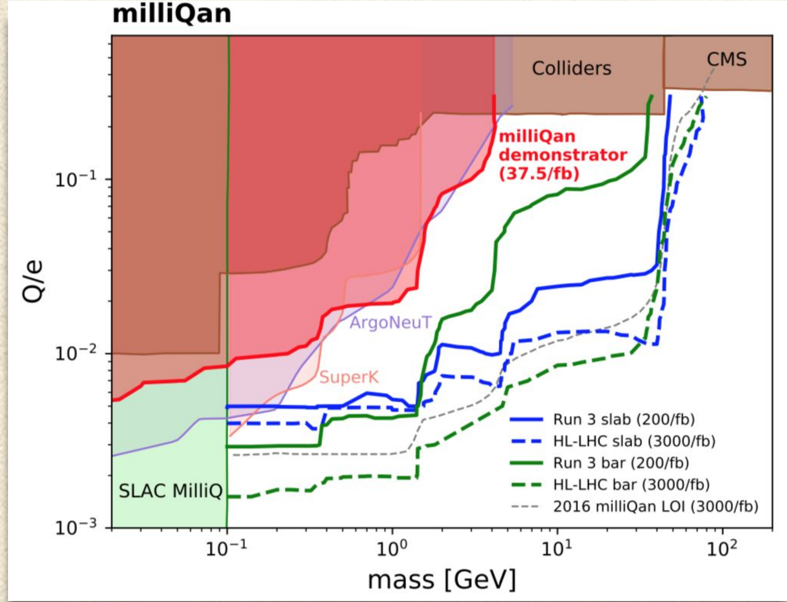
- 17 m rock shielding, 1x1x3 m^3 plastic scintillator array + high-gain PMTs with long axis pointing to CMS IP
- Small prototype (~1% size) took data in 2018 (and confirmed background expectation)
- Two Run 3 detectors

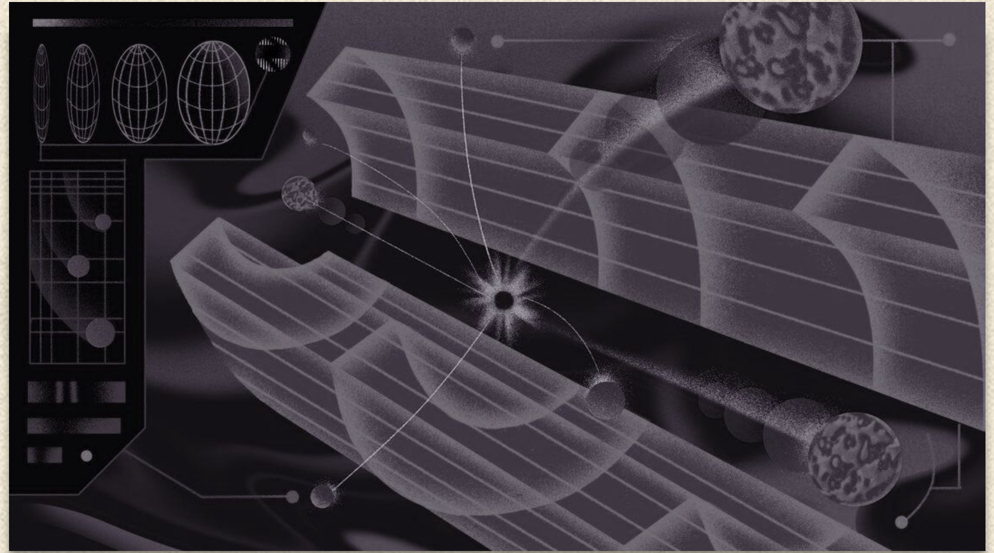
Demonstrator upgrade: more bkg studies



40x60x5 cm scintillator slabs → help improving sensitivity for bigger and to further reject bkg







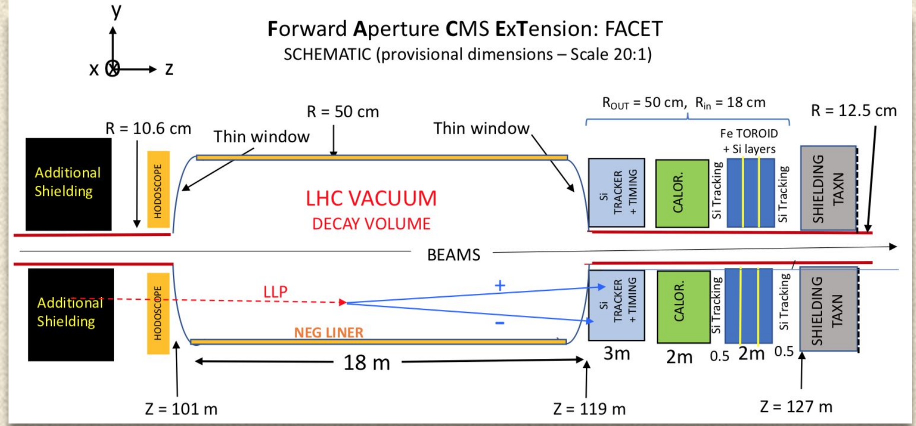
04

Forward LLP detectors

FASER: see Monica's talk

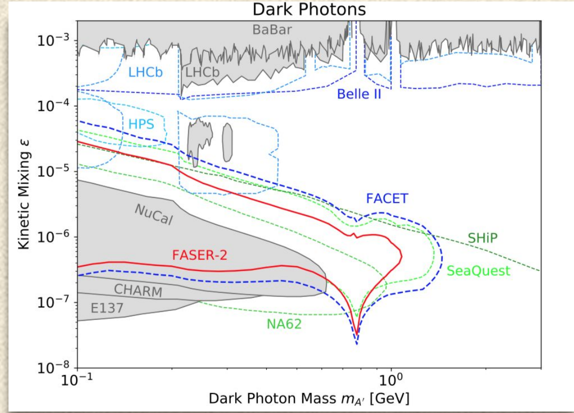
arXiv:2201.00019 (proposal)

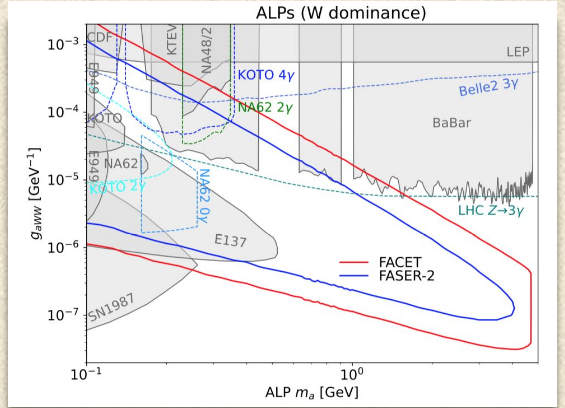
FACET

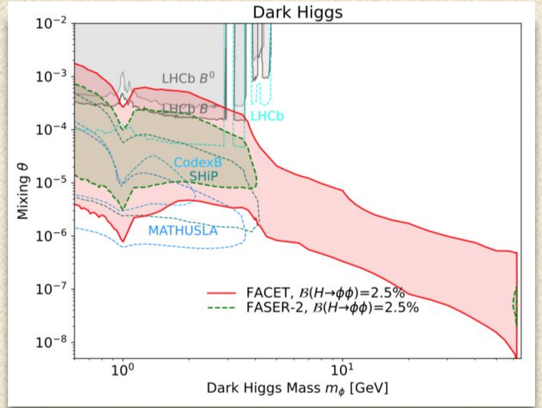


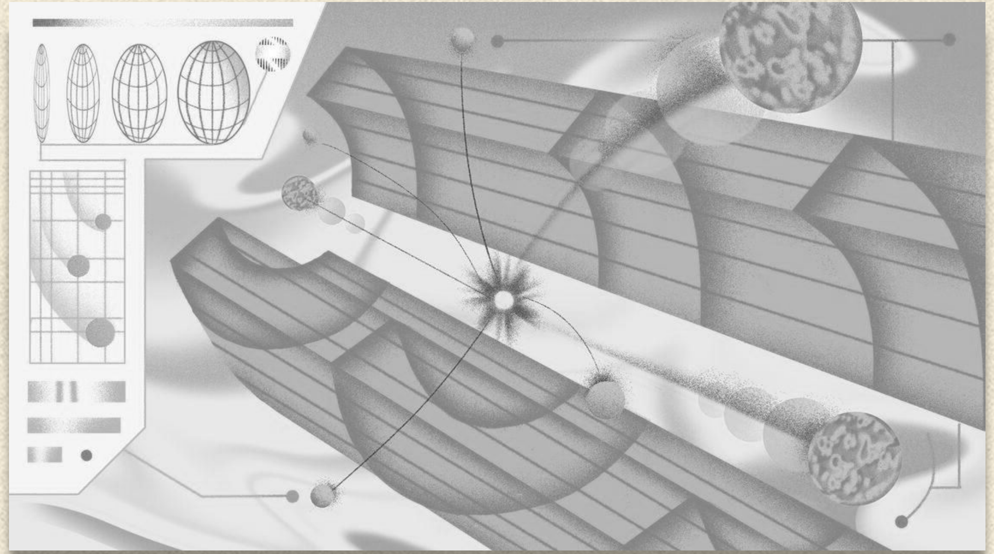
Forward- **A**perture **C**MS **E**x**T**ension

- Replace 18 m long section of the LHC beam pipe on one side of the interaction region with a circular pipe of 50 cm radius
  1. Additional shielding placed upstream of the first detector hodoscope (made of radiation-hard quartz pads)
  2. Silicon trackers + timing and calorimeters (as CMS Phase-2 upgrade) to measure the LLP decay products
  3. Iron toroid (1.75 T) with additional silicon trackings







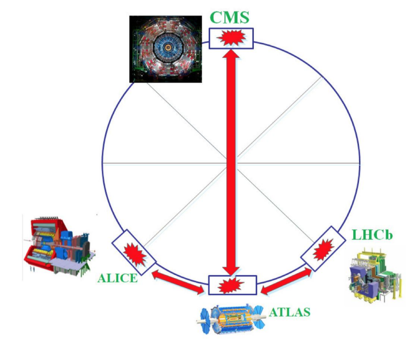


05

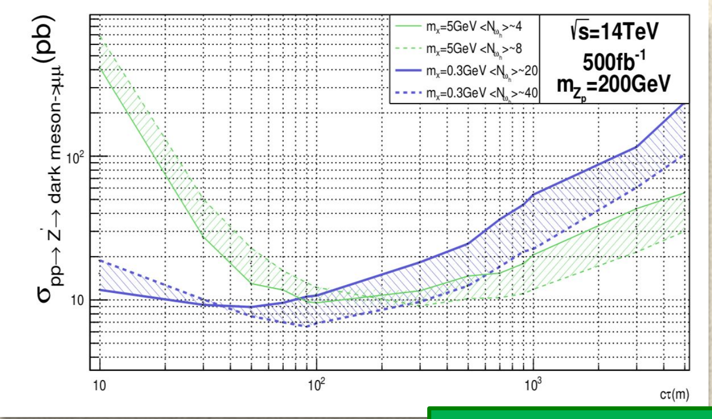
Some Other New Ideas

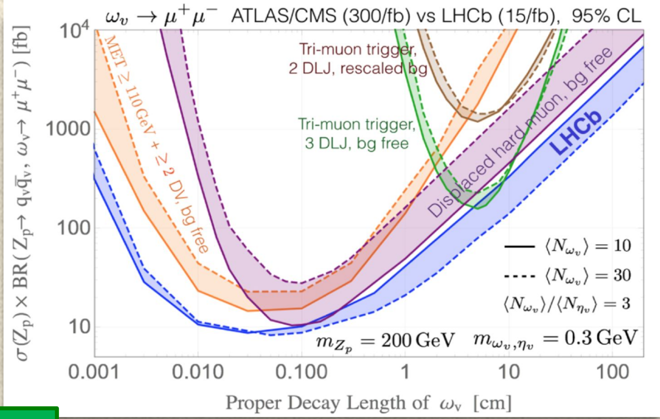
LHC Detector Array for LLP

Use the ATLAS detector (biggest muon system) to detect di-μ LLP decays from other detectors



- Main backgrounds from
  - Cosmic muons / bkg from collisions (removed using directional information)
  - Radioactive environment (removed: muon pt > 1 GeV)
  - High energy muons from LHCb/ALICE, neutrino conversion (expected to be negligible)





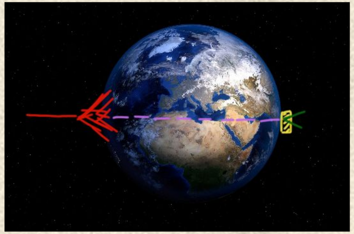
Different lifetime range

From Phys Rev D 97 095033

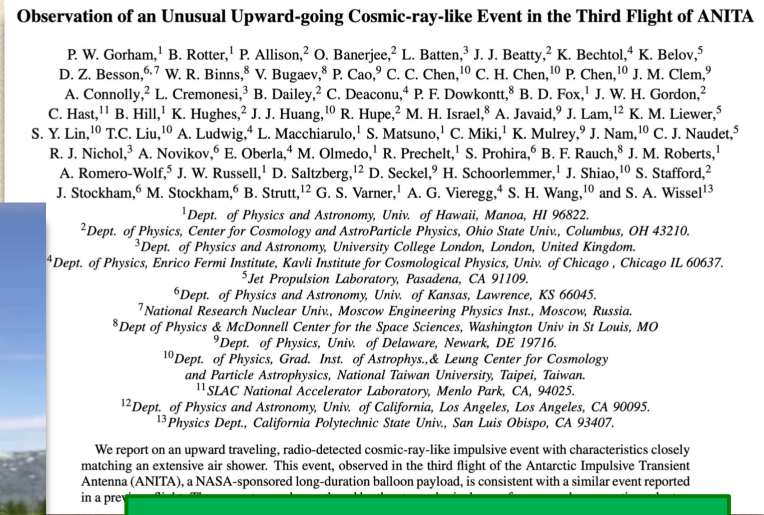
LLP in Cosmic Rays

LLP with masses ~GeV can be produced in hadron decays

- Possibly produced in a cosmic ray showers even without TeV-scale mediator
- LLP flux need to be quantified for every model
- Cosmic ray from all directions can contribute
- In principle no detector necessary and dedicated searches can already be sensitive (?)



Many theoretical discussions
arXiv:1906.09064
arXiv:1910.12839
arXiv:1806.03063



Observation of an Unusual Upward-going Cosmic-ray-like Event in the Third Flight of ANITA

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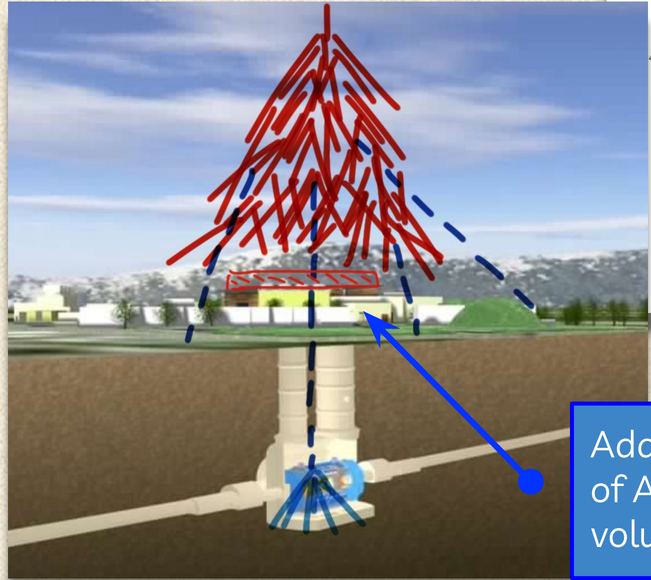
We report on an upward traveling, radio-detected cosmic-ray-like impulsive event with characteristics closely matching an extensive air shower. This event, observed in the third flight of the Antarctic Impulsive Transient Antenna (ANITA), a NASA-sponsored long-duration balloon payload, is consistent with a similar event reported in a pre

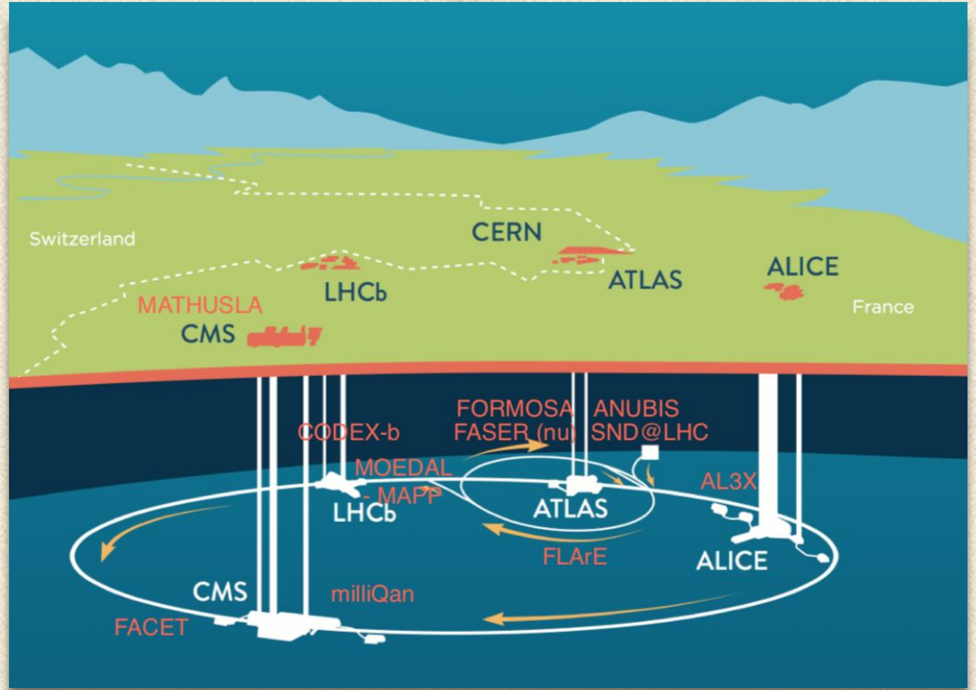


Maybe can explain ANITA excess?

Adding a layer of RPC/scintillator on top of ATLAS roof and use to create a decay volume between surface-ATLAS?

Conclusions

- Impressive number of complementary detectors
- Can make the LHC LLP search program more comprehensive
- Can have the potential to significantly enhance and extend the new physics reach and capabilities of the current LHC detectors
- More ideas may come soon…



Backup

Comparison of Detector Design – Neutral LLP

	Collision point	Distance from IP	Fiducial volume	Use main experiment?	Shielding cosmics	Shielding collision	Technology
MATHUSLA	CMS	~90 m	25m x 100m x 100m	Under study	NO	YES	Scintillators (+ 1 RPC)
ANUBIS	ATLAS	~25 m	~56m x $(9m)^2$	YES	Partial	NO	RPC (scintillators to be explored)
CODEX-b	LHCb	~35 m	10m x 10m x 10m	Under study	YES	YES	RPC
AL3X	ALICE	~4.25 m	~12m x $(2.5m)^2$	NO	YES	YES	Gas TPC

- For a given decay volume,
  - More solid angle if closer to the IP
  - Number of decays higher if closer to the IP
  - LHC collision backgrounds more important if closer to the IP (depending on shielding)

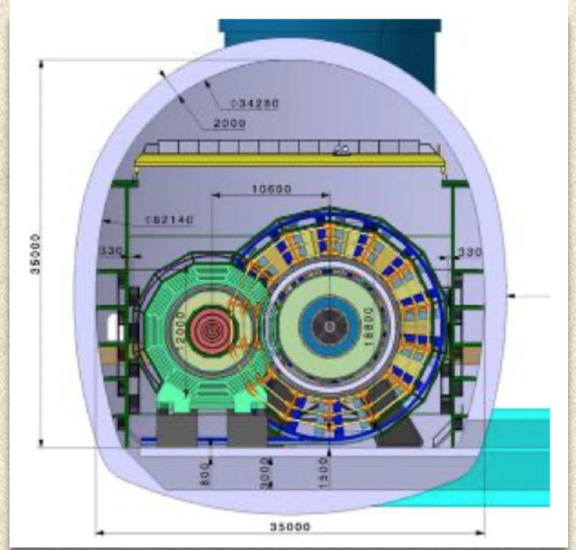
Credits: Emma Torró

arXiv:2011.01005 (proposal)

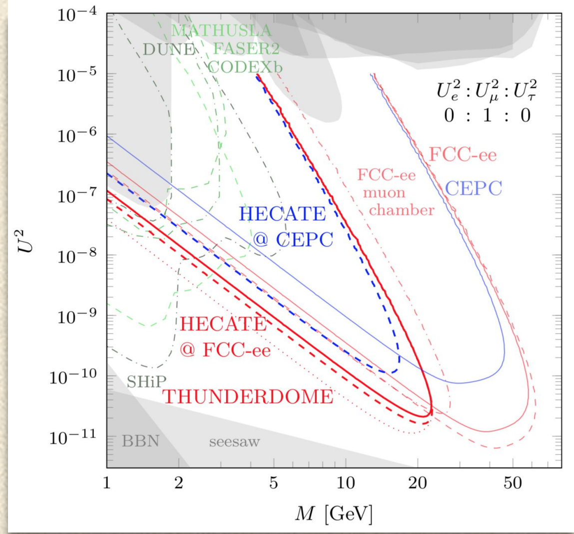
LLP @ FCC-hh and FCC-ee

HErmetic **CA**vern Track**ER**

- FCC-hh / FCC-ee main detectors will be relatively smaller than the cavern
- Cover detector cavern walls with scintillator plates or RPCs
  - Use FCC detector as active veto
  - >= 2 layers of 1 m^2 separated by a sizeable distance
  - >= 4 layers for good tracking



Cavern size: r~15 m and z~50 m
Main detector size = 10m

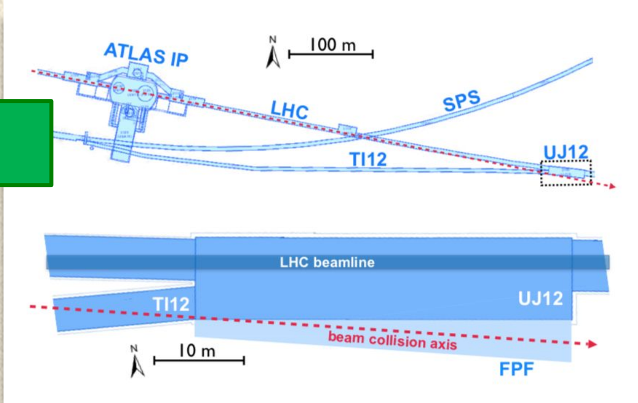


THUNDERDOME = Totally Hyper-UNrealistic DEtectoR in a huge DOME

Formosa

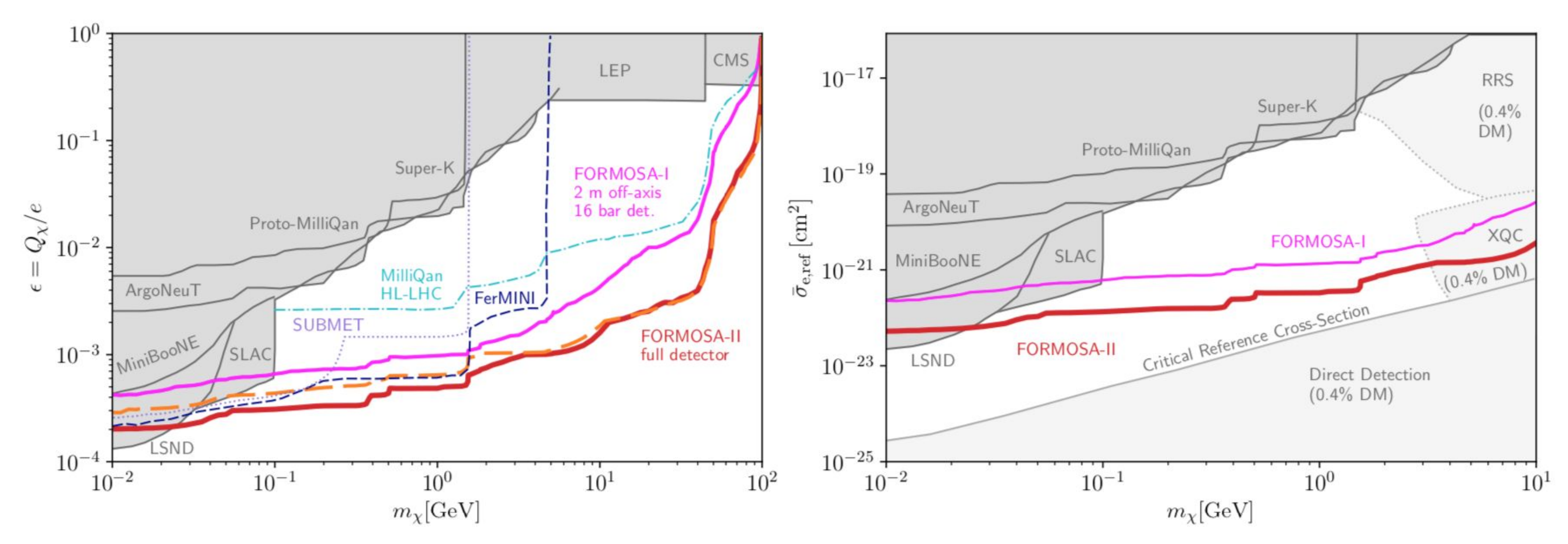
arXiv:2010.07941 (proposal)

World's most sensitive location



FOrward MicrOcharge SeArch

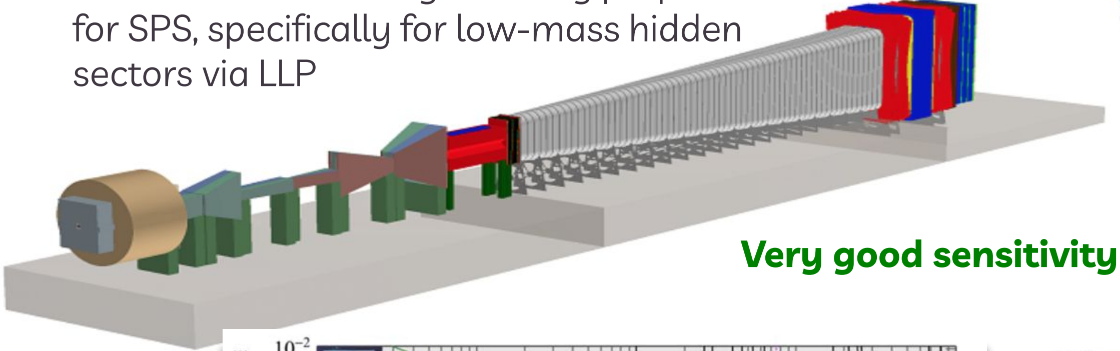
- Looking for millicharge particles in the 10 MeV -100 GeV region in a large and unexplored parameter space and study strongly interacting DM
- Scintillator based experiment (similar to Milliqan)

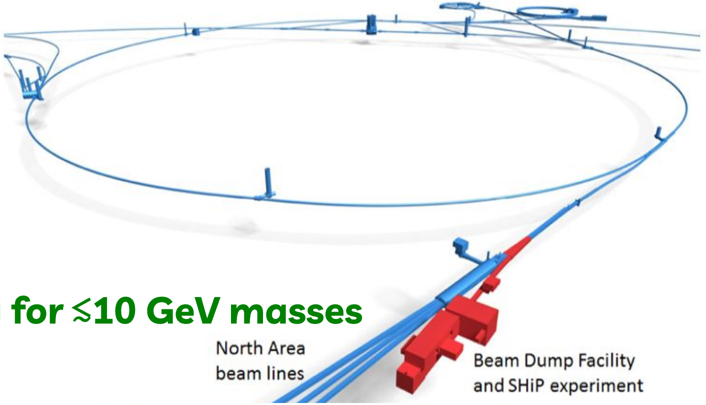


North Area Experiments – SHiP

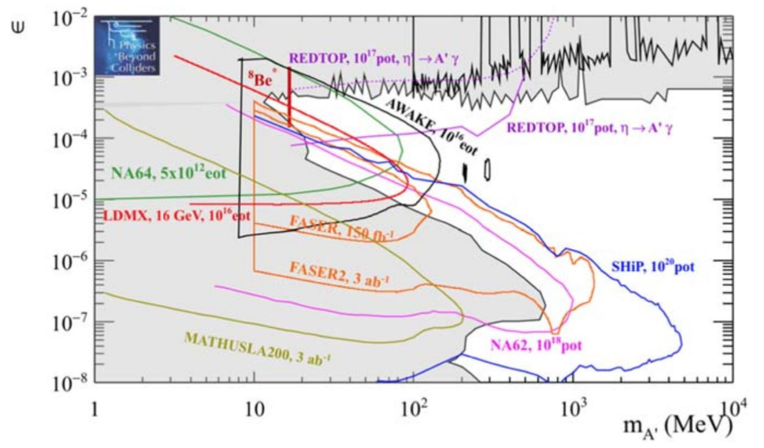
Search for **Hi**dden **P**articles

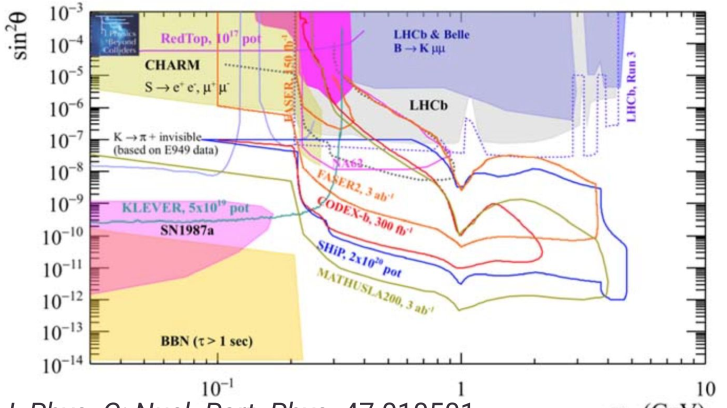
- √s = 38 GeV fixed target facility proposed for SPS, specifically for low-mass hidden sectors via LLP





Very good sensitivity for ≲10 GeV masses





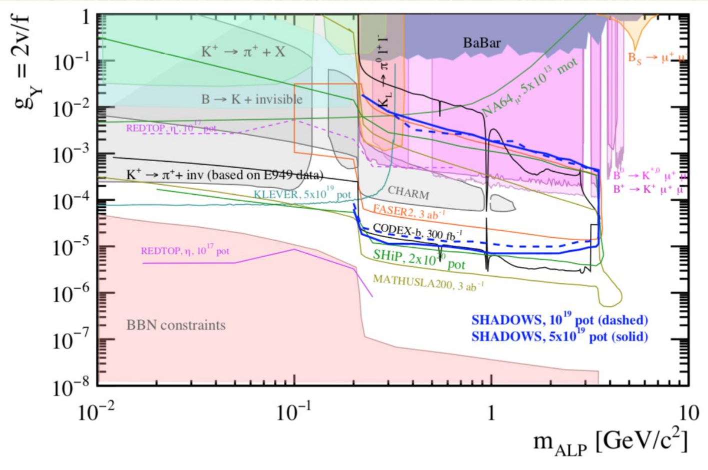
J. Phys. G: Nucl. Part. Phys. 47 010501

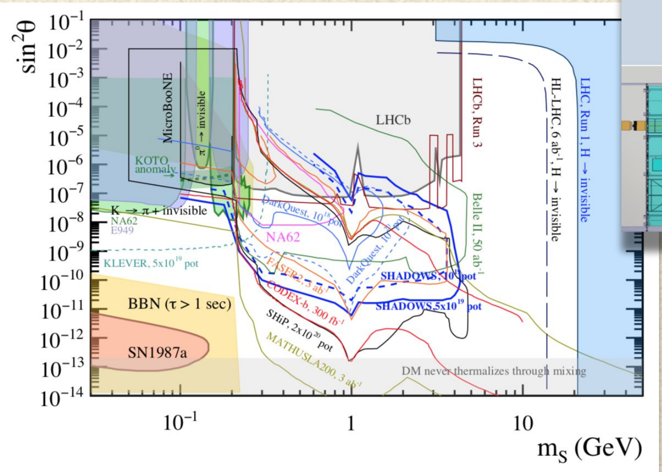
North Area Experiments – SHADOW

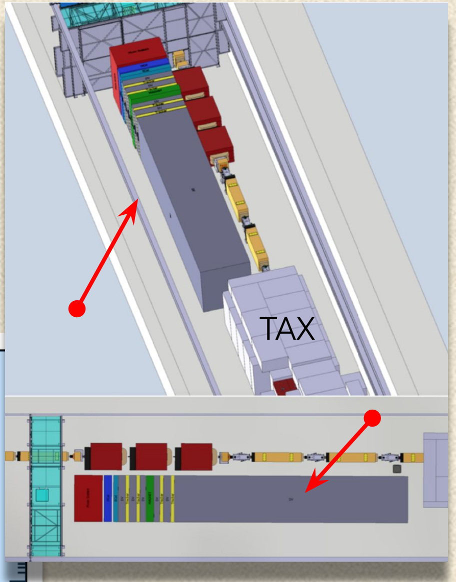
(expression of interest)
https://cds.cern.ch/record/2799412

Search for **Hi**dden **P**articles

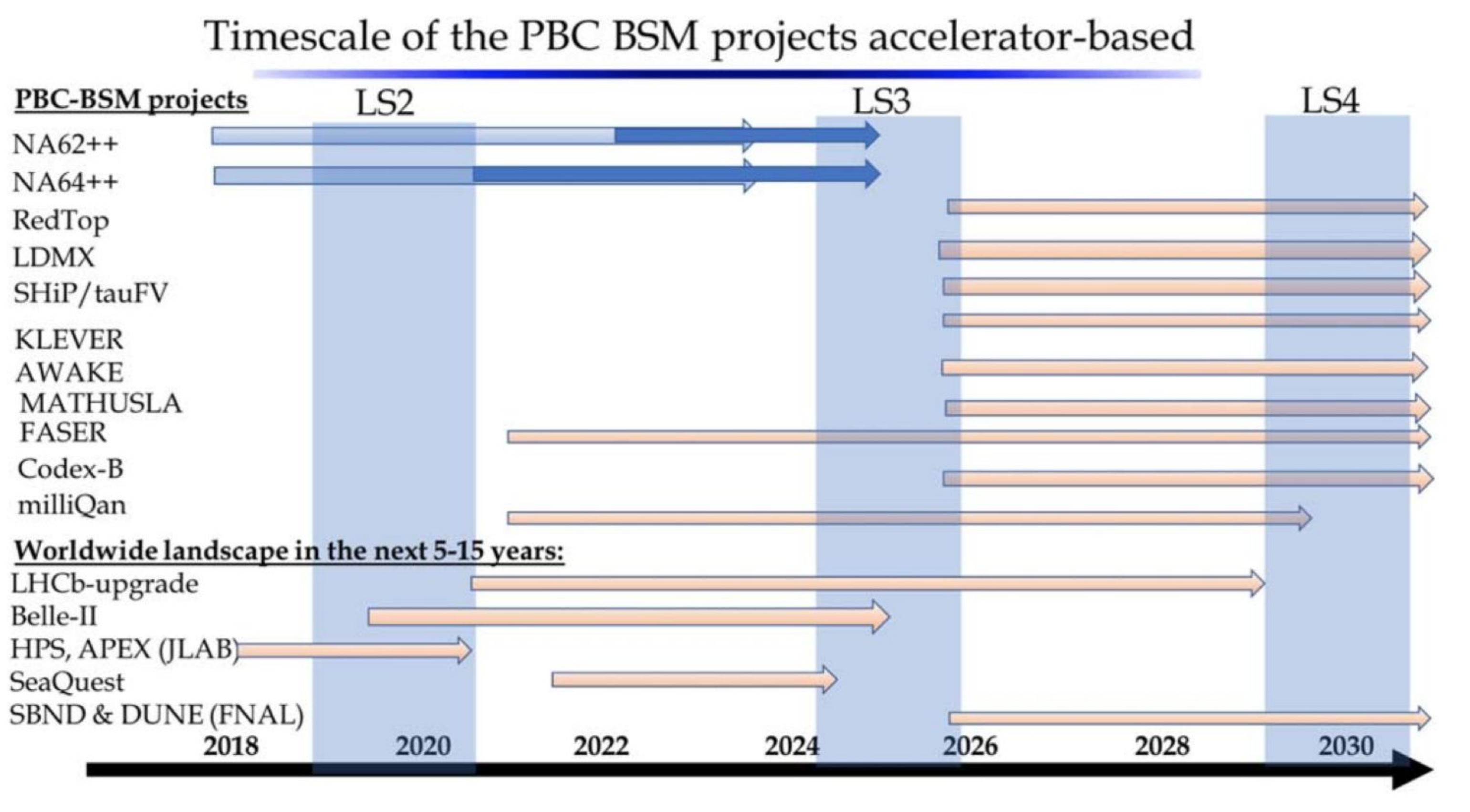
- Proposal for a beam dump experiment to complement NA62 beam dump facility
- “Low cost” detector installed slightly off axis of the TAX shield zone
  - Less affected by μ/ν bkg from beam interaction with dump
  - Series of decay volumes + muon spectrometers
- ~10^9 protons/year on target to study a large variety of FIPs in the mass range MeV-GeV
  - Strongest bounds exist up to K mass; above bounds weaken significantly







Some Rough Timeline



HL-LHC Forward Facility

Proposal to build dedicated forward physics facility for HL-LHC