Searches for long-lived particles at future colliders

INSTITUTE OF PARTICLE PHYSICS

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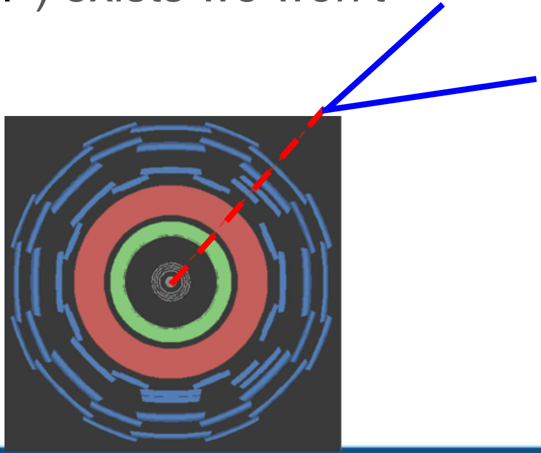
What are (neutral) LLPs

- In current general purpose detectors, most standard model particles produced stop in the detector, with muons and neutrinos being the notable exceptions
- The muon is unstable, with a lifetime around $c\tau \approx 700$m
- The muon is therefore an “ultra long-lived particle” ($c\tau > 10^1$m & $c\tau < 10^7$m)
- If a weakly coupled neutral long-lived particle (LLP) exists we won’t necessarily see it decay within modern detectors

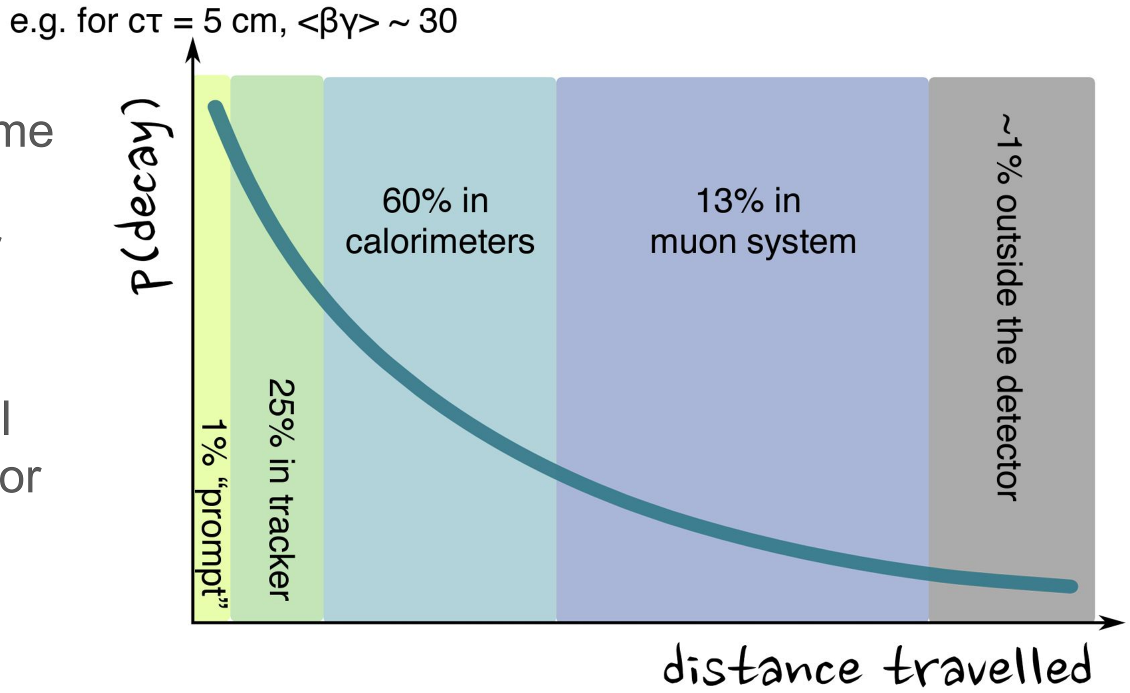
Muon escape



LLP escape and decay

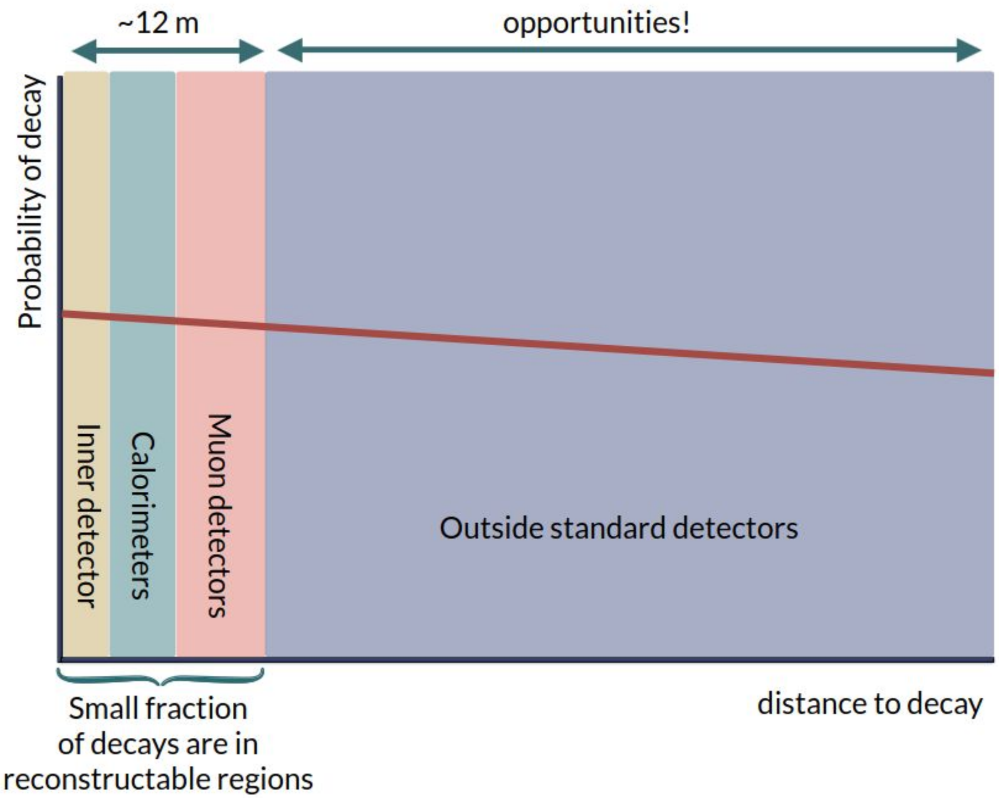
Searching for LLPs

- Depending on the lifetime of LLPs, they may still decay within a detector but require dedicated searches
- Longer lifetimes will still decay within the detector but the probability continually drops

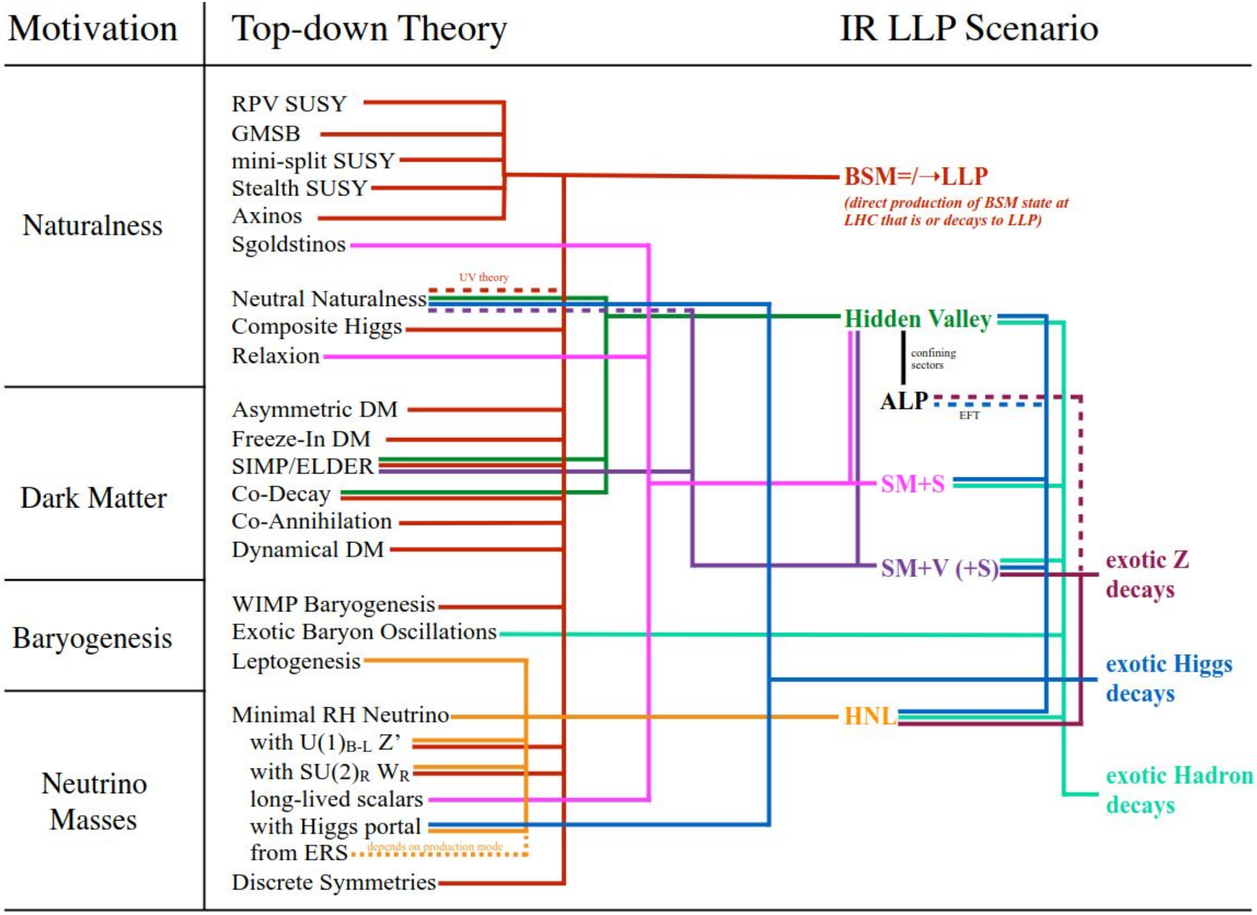


Collider Opportunities

- $c\tau$ for LLPs could be up to 10^7 m
- With HL-LHC and FCC, the infrastructure to produce LLPs **will already exist**
- We just need detectors



Neutral Long Lived Particle (LLP) Motivations

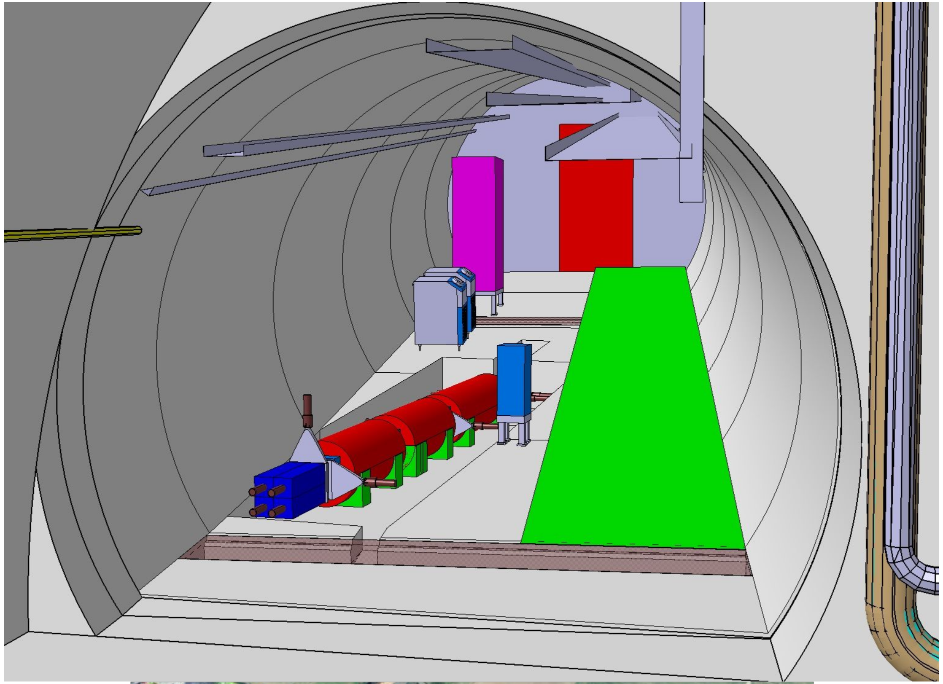


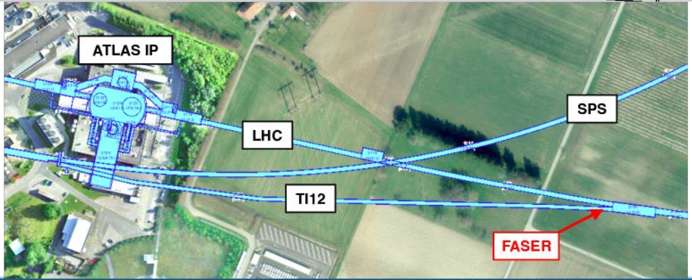
Why Future Colliders?

- FASER taking data in the forward direction on the LHC
- SHiP approved to be built on the SPS
- ATLAS/CMS have active LLP analyzes
- All sensitive to LLPs, why do we need more?
    - FASER limited to forward direction/ limited size
    - SHiP can’t produce Higgs, no couplings to Higgs portals
    - ALTAS/CMS limited by cτ

FASER

- Squished into an access tunnel a few hundred metres from ATLAS
- Searches for BSM physics through **LLPs**
    - dark photons, dark Higgs bosons, and heavy neutral leptons
- Also detects neutrinos from the collision (link)
- A larger iteration, FASER 2, is being considered for HL-LHC

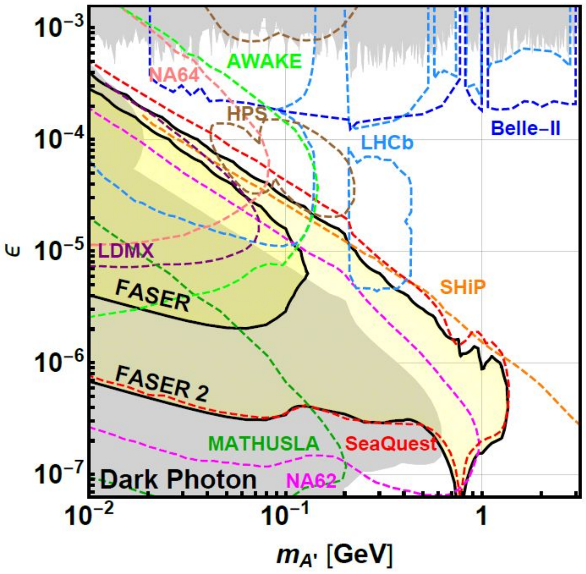




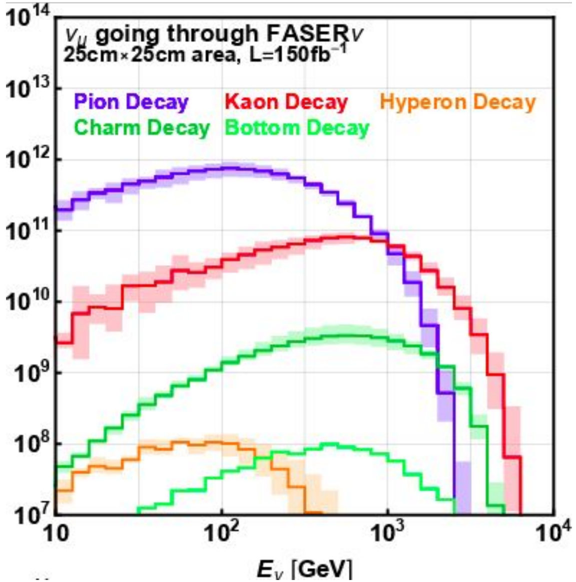
existing detector

FASER Physics

plots from:faser.web.cern.ch

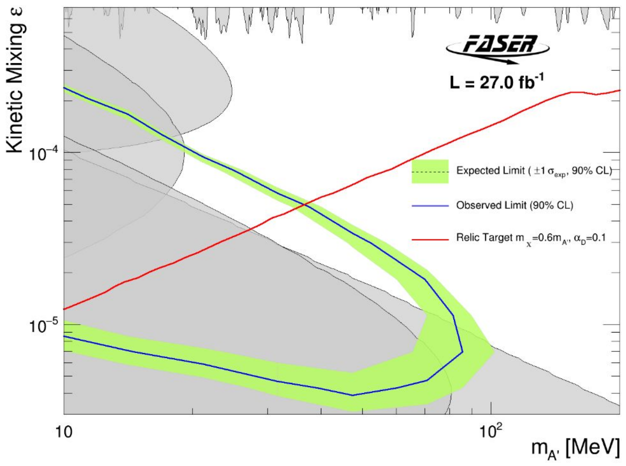


Exclusion curve for a dark photon with coupling ϵ, and mass m

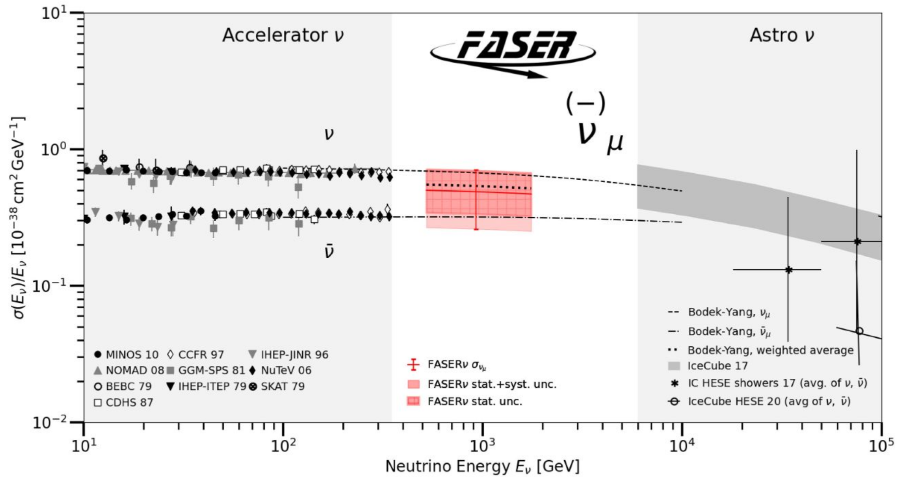


Estimated number of muon neutrinos passing through FASER

FASER Physics **results**



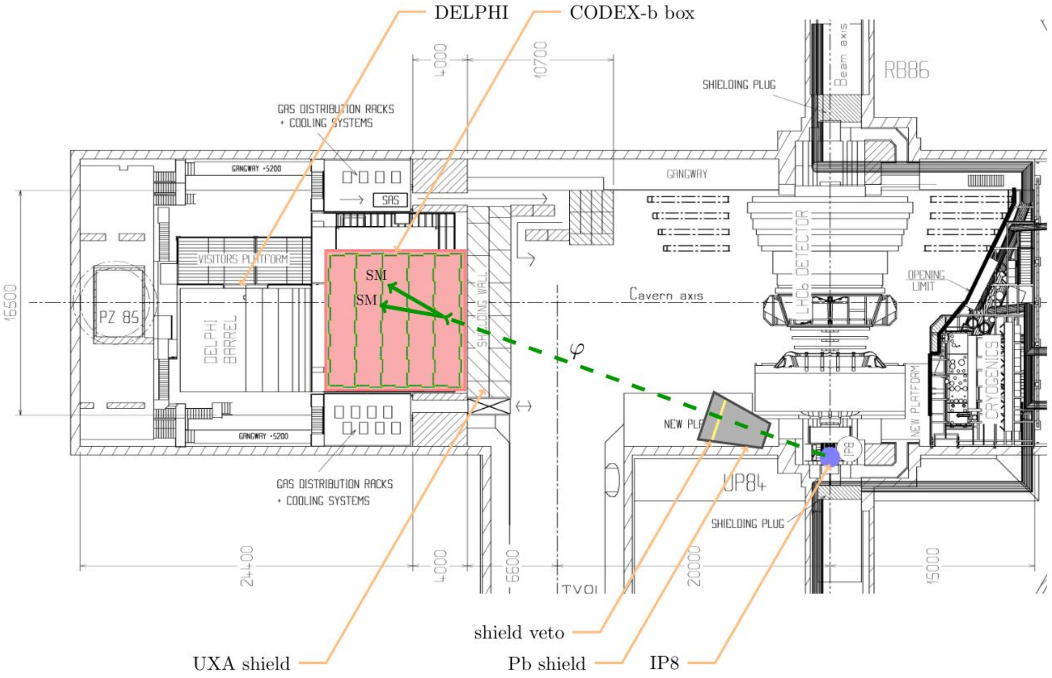
Exclusion curve for a dark photon with coupling ϵ, and mass m
DOI:10.22323/1.449.0039



muon neutrino cross-section as a function of energy
DOI:10.1103/PhysRevLett.133.021802

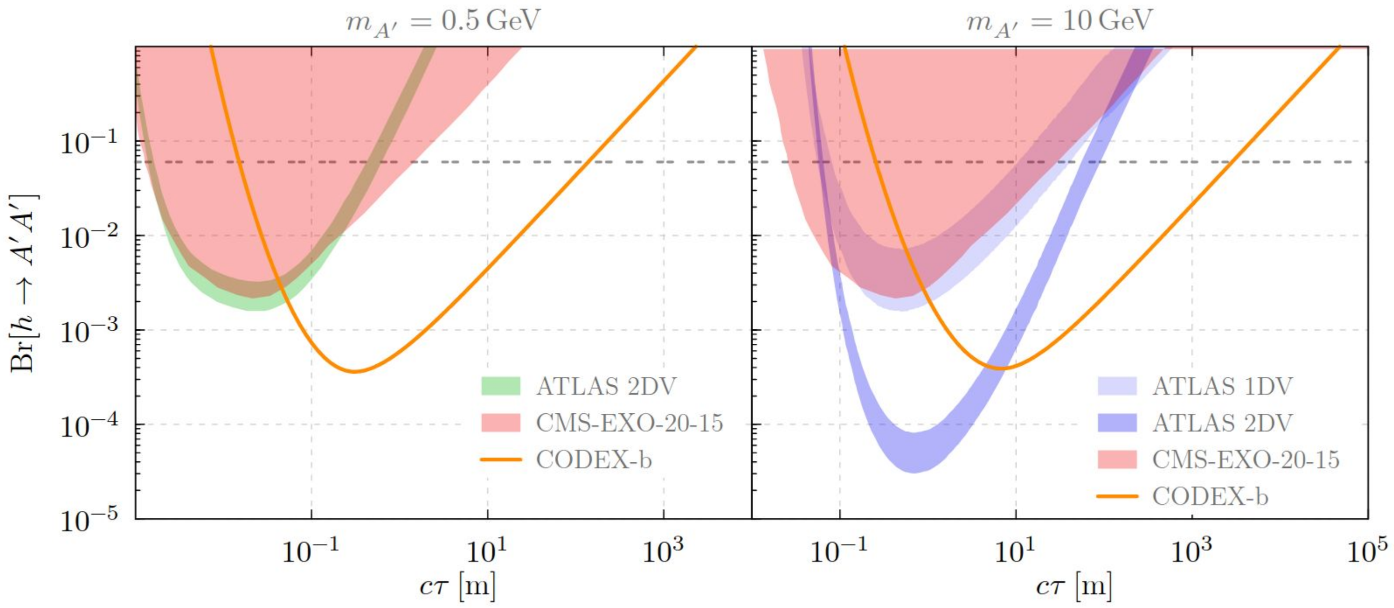
CODEX-B

- Squished into a maintenance area near LHCB
- Searches for BSM physics through LLPs
- Limited by available space and luminosity delivered



CODEX-B Physics

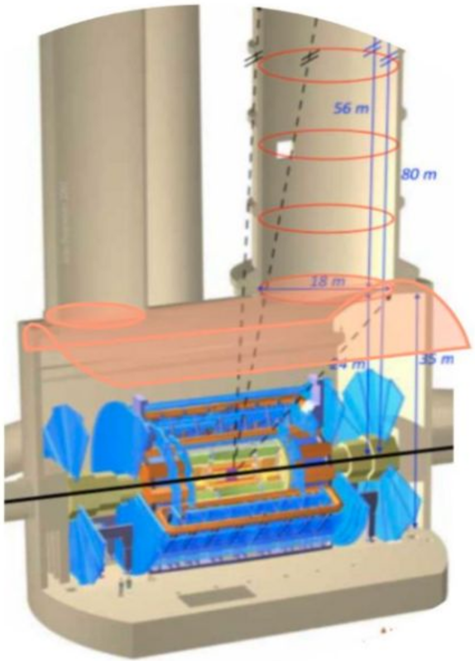
plots from:arxiv.org/abs/2203.07316

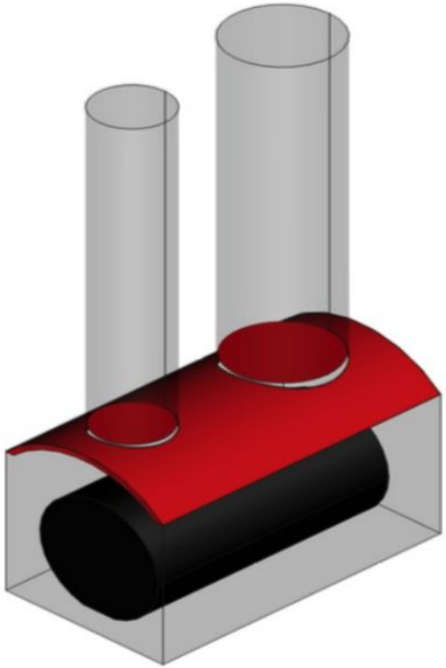


Sensitivity to the Higgs to dark photon branching fraction as a function of lifetime

ANUBIS

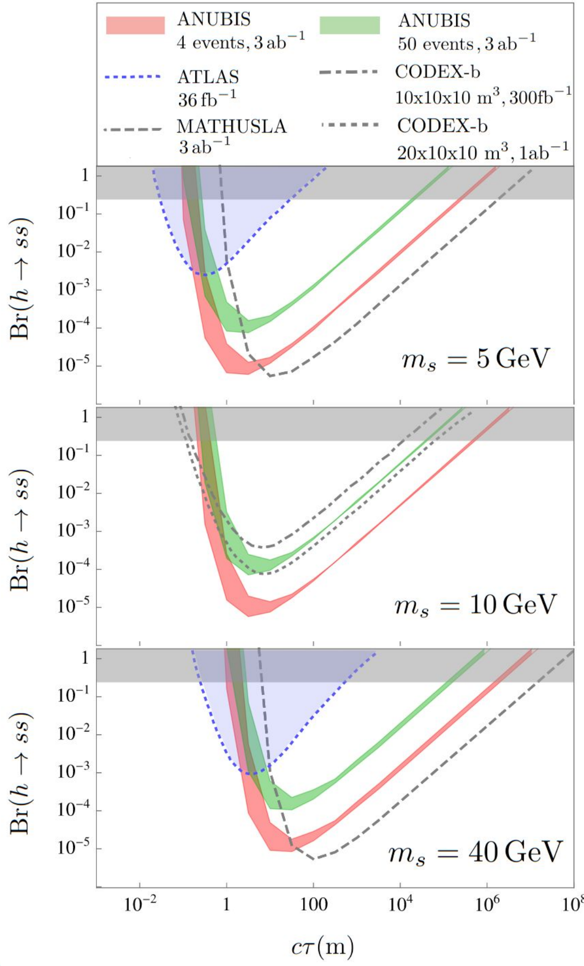
- Squished into the space above ATLAS
- “easy” external triggering of ATLAS for combined analysis
- Two possible configurations
    - Shaft
    - Ceiling





ANUBIS Physics

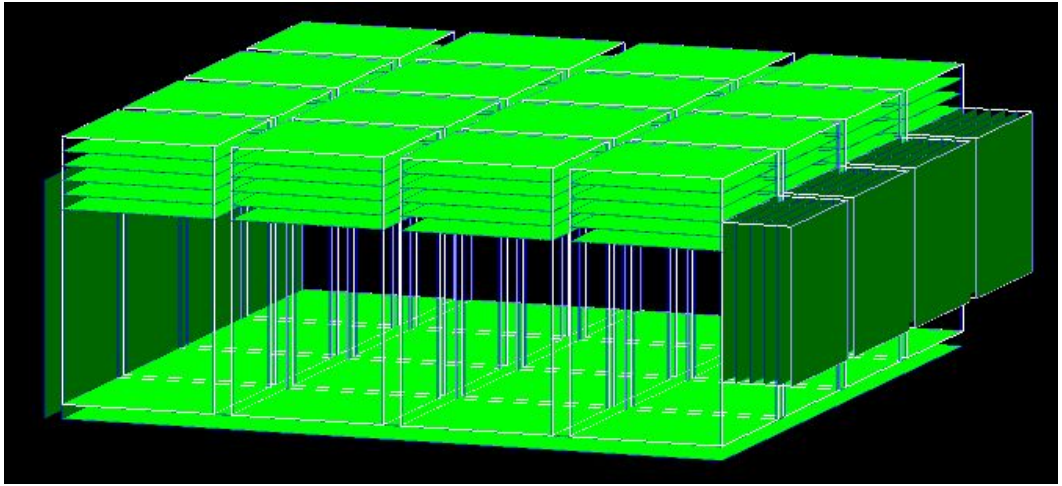
Sensitivity to the branching fraction of Higgs to long lived scalar as a function of lifetime and scalar mass



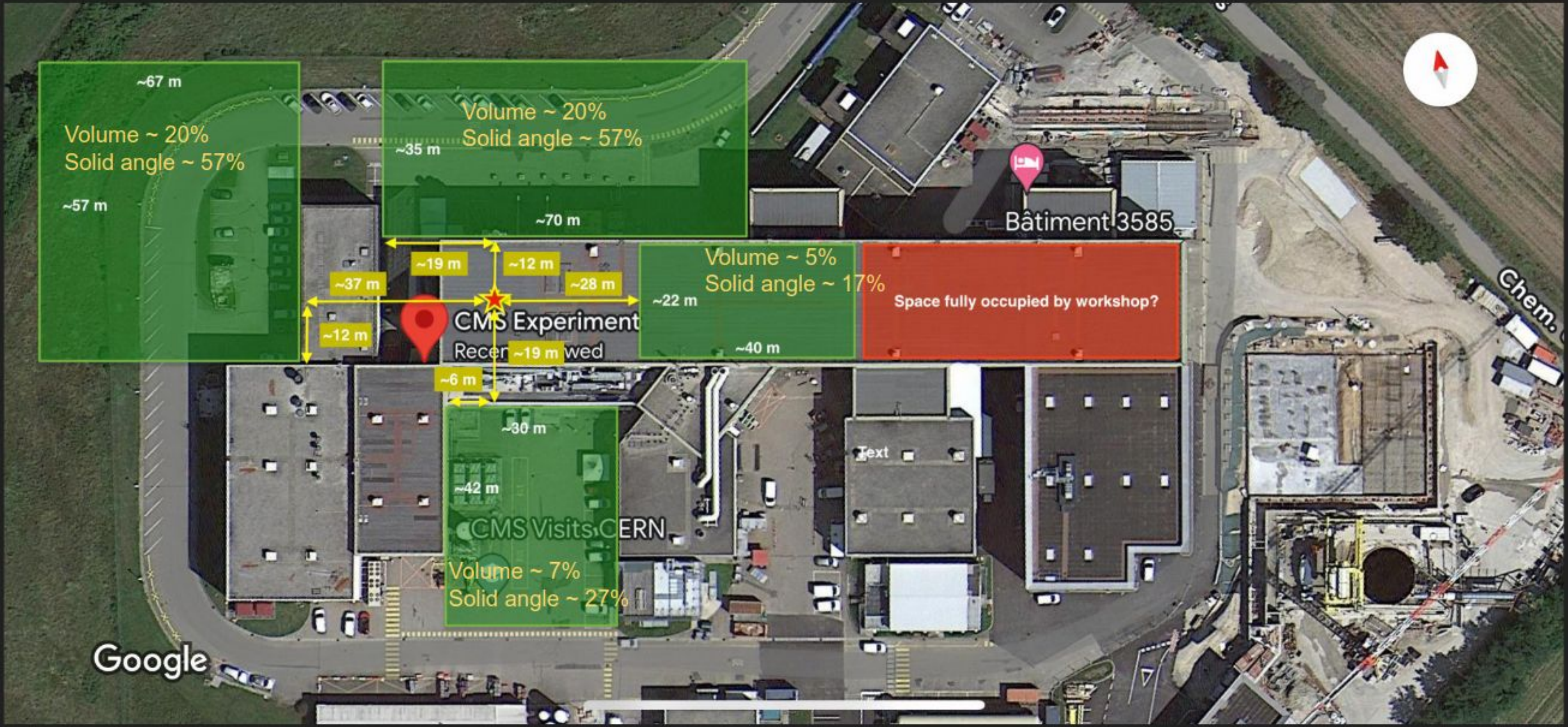
plots from:arxiv.org/abs/1909.13022

MATHUSLA

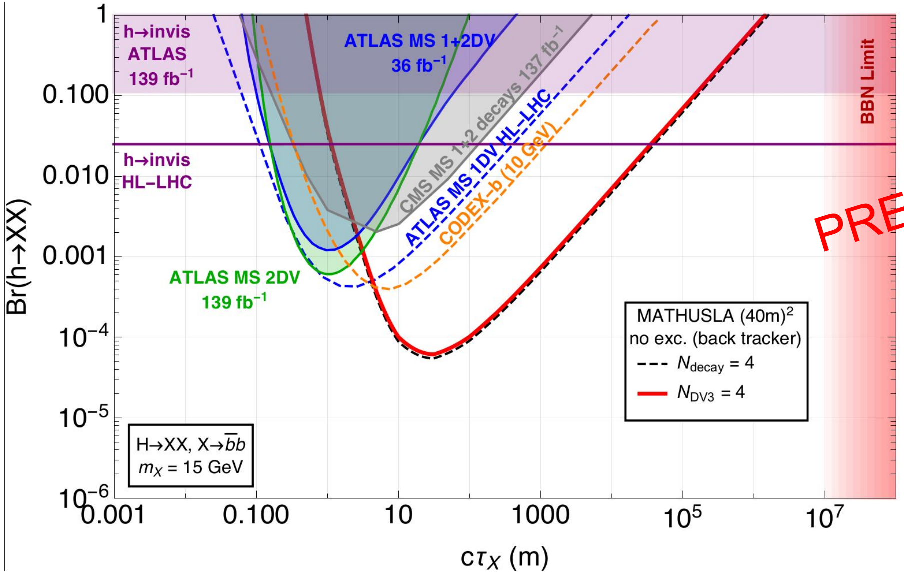
- MATHUSLA40 is a descoped version of prior proposals. 40m x 40m x 17m
- Being a surface detector allows for limited-“unlimited” space
- Ideally, positioned directly above ATLAS or CMS to maximize solid angle
- Floor/Wall layers detect incoming standard model particles
- Top/Wall layers search for the appearance of standard model particles



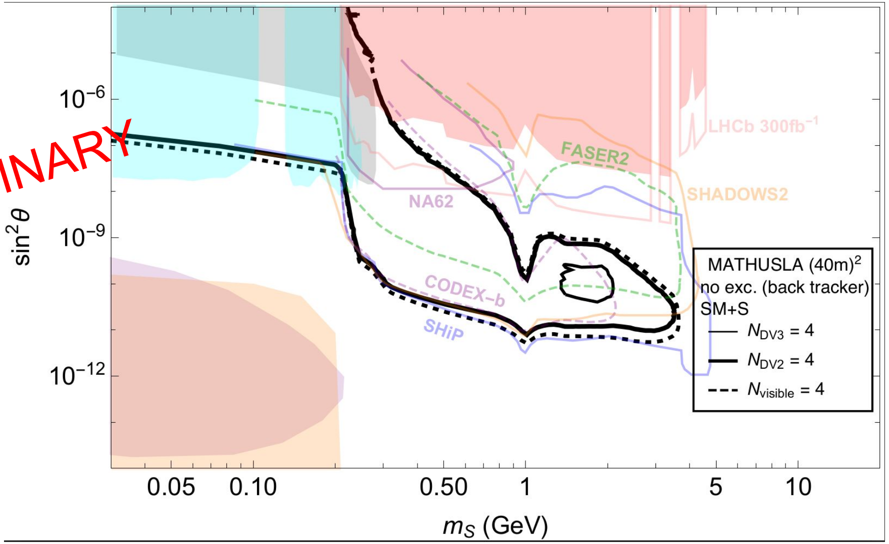
Trying to fill the empty spaces around CMS



MATHUSLA Physics



Sensitivity to the branching fraction of Higgs to exotic as a function of lifetime



Exclusion curve for the coupling to a LLP scalar as a function of scalar mass

Why these experiments?

- Space is a precious commodity around the LHC
- Maximizing the use of space in:
  - Access tunnels (FASER)
  - In adjoining maintenance/experimental space (CODEX-B)
  - Above detectors (ANUBIS)
  - On the surface (MATHUSLA)
- Takes advantage of the existing environment at the LHC (HL-LHC) instead of building a dedicated facility

Maximizing Existing Infrastructure

Building dedicated facilities is expensive

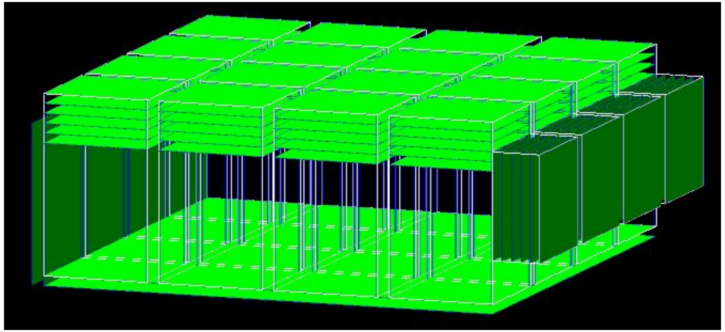
SNOLAB~$100M	TRIUMF~$?	LHC~$4B	FCC~$20B
HALO DAMIC FLAME	DarkLight PIENU Test Beams	FASER CODEX-B ANUBIS MATHUSLA	???

Important to maximize the physics potential of our facilities, going beyond the flagship experiments

What can we do better at the FCC?

Demonstrator
(LHC)

Experiment
(HL_LHC)



Large(er) Experiment
(FCC)

?

Future of LLP projects

- Between all the current proposed LLP experiments, a variety of detector technologies will (hopefully) be tested
- As a community should be down-select to one or two of the most promising for a larger scale implementation at the FCC?
  - If we discover something, can then construct a detailed measurement machine
- We should be actively engaging with the CERN Physics Beyond Colliders group to make space needs clear before construction begins
  - Dedicated underground space near a collision point? (large solid angle, low $c\tau$)
  - Surface building? (small solid angle, larger $c\tau$)
  - Additional electrical, internet, safety services

Future of LLP projects

- How can we coordinate with future flagship projects
    - Designing DAQ with external triggers in mind
    - Ensuring enough buffer space exists to save data from external triggers
    - Can muon detector design be integrated with LLP goals
    - Connection to the LHC clock

Conclusions

- LLP physics is being approached in many ways
- Each experiment struggles in it's own way to maximize sensitivity
    - Constraints lead to creativity
- The LLP parameter space is vast and will likely require a large scale detector to adequately probe
- LLP experiment(s) will be present at the FCC, can we design for them