



# FIPs at Large Angle: ANUBIS, CODEX-b, and MATHUSLA



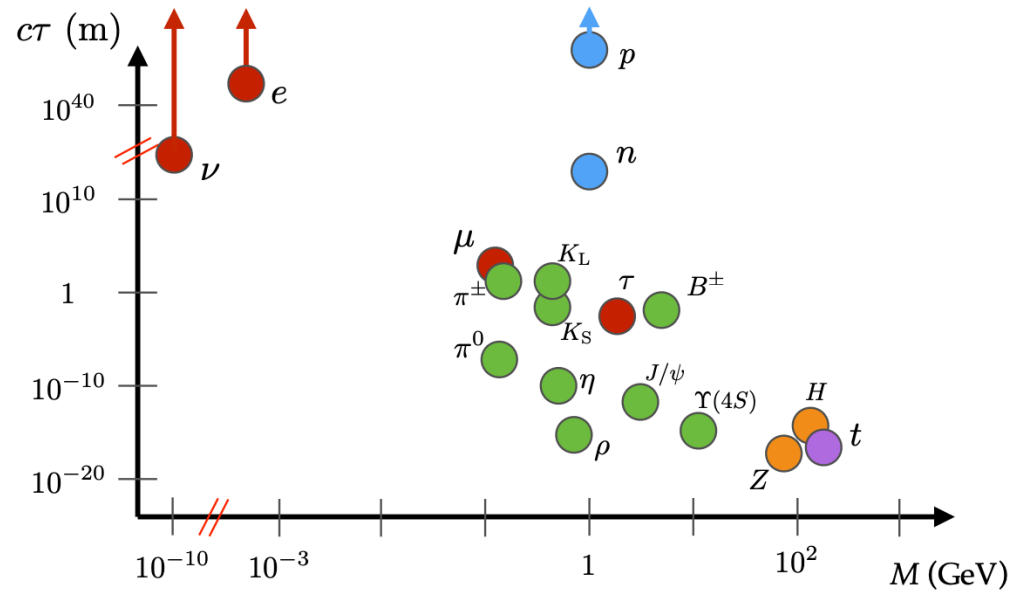
**Juliette Alimena** (DESY), on behalf of the ANUBIS, CODEX-b, and MATHUSLA Collaborations

Physics Beyond Colliders Annual Workshop, CERN

November 8, 2022

# Long-Lived Particles (LLPs)

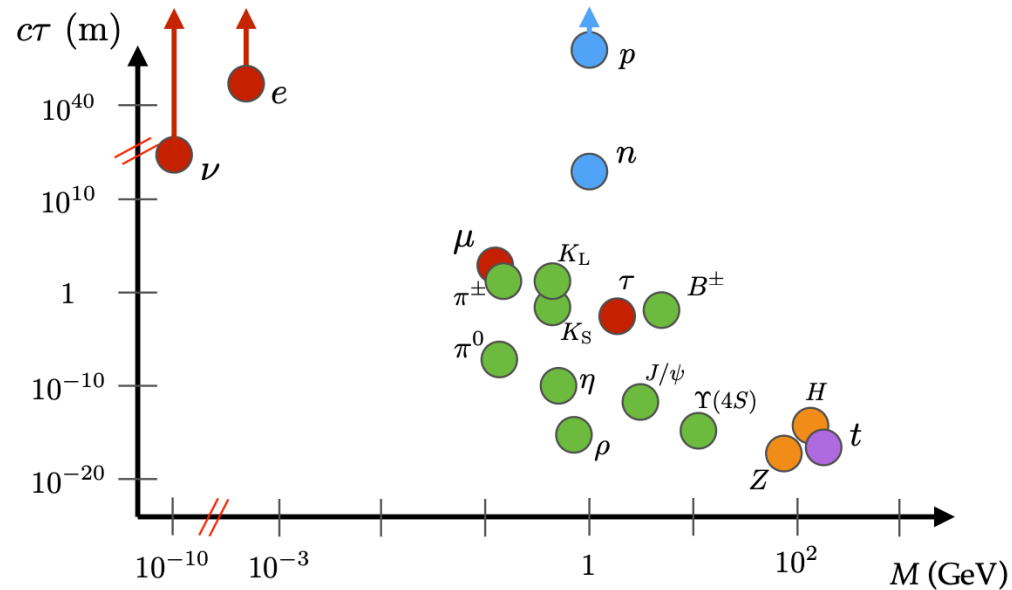
Standard model particles span a  
wide range of lifetimes ( $\tau$ )





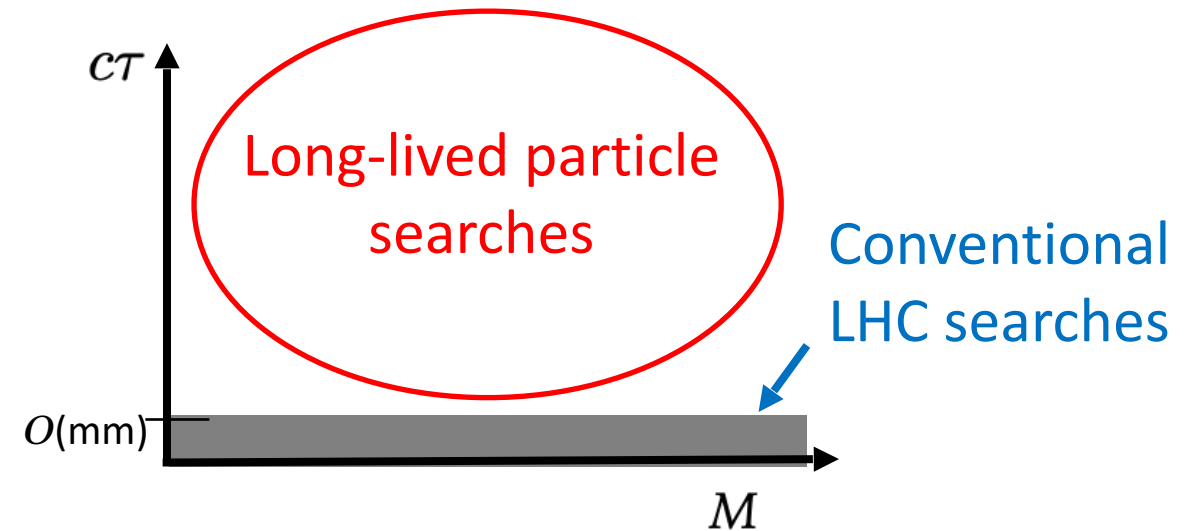
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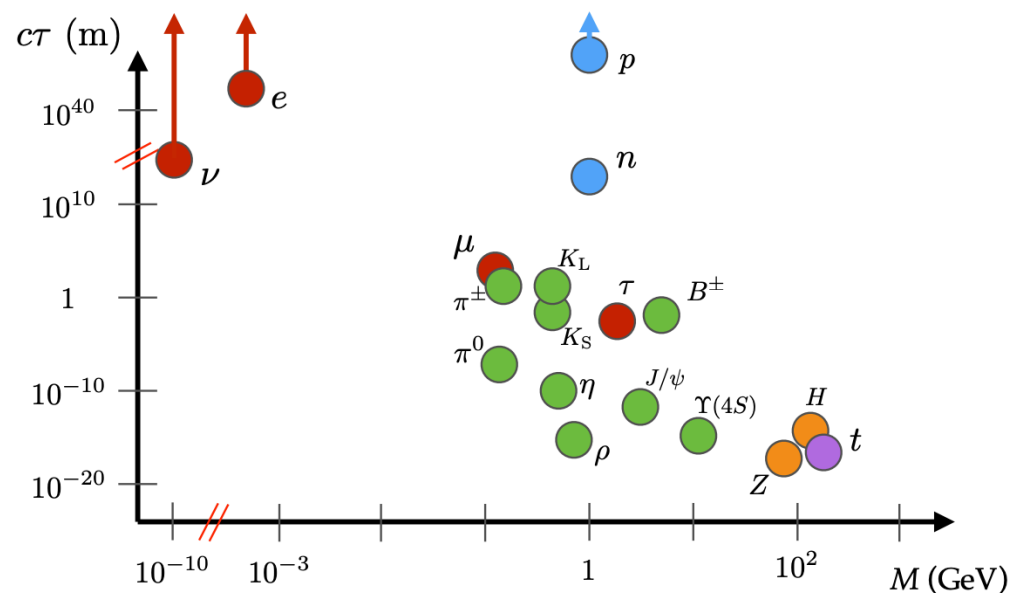
We expect **new phenomena** to have a wide  
range of lifetimes as well

But **conventional searches** for new phenomena  
at the LHC are for **promptly** decaying particles



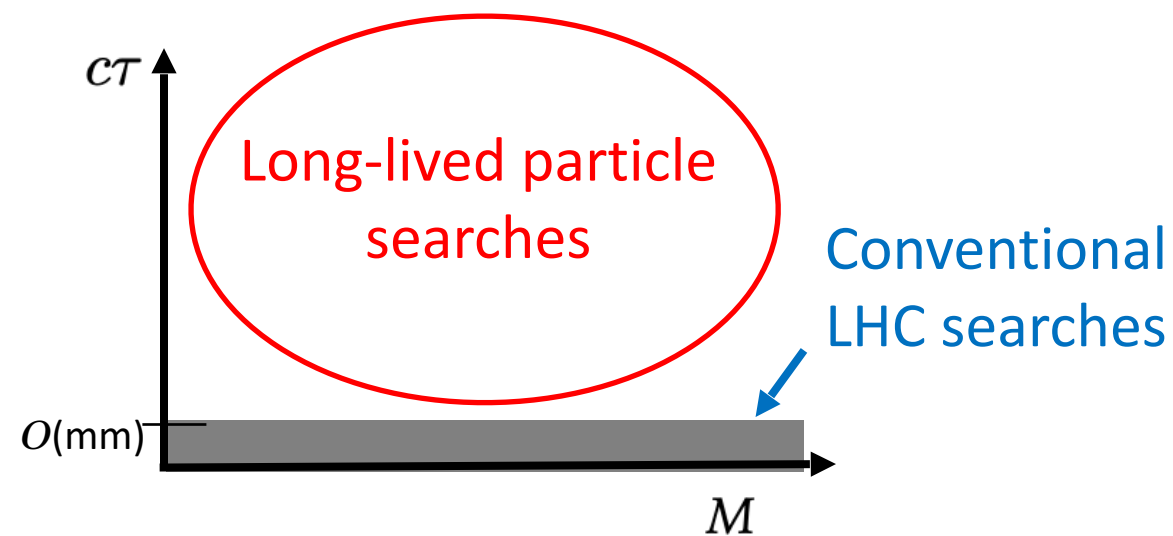
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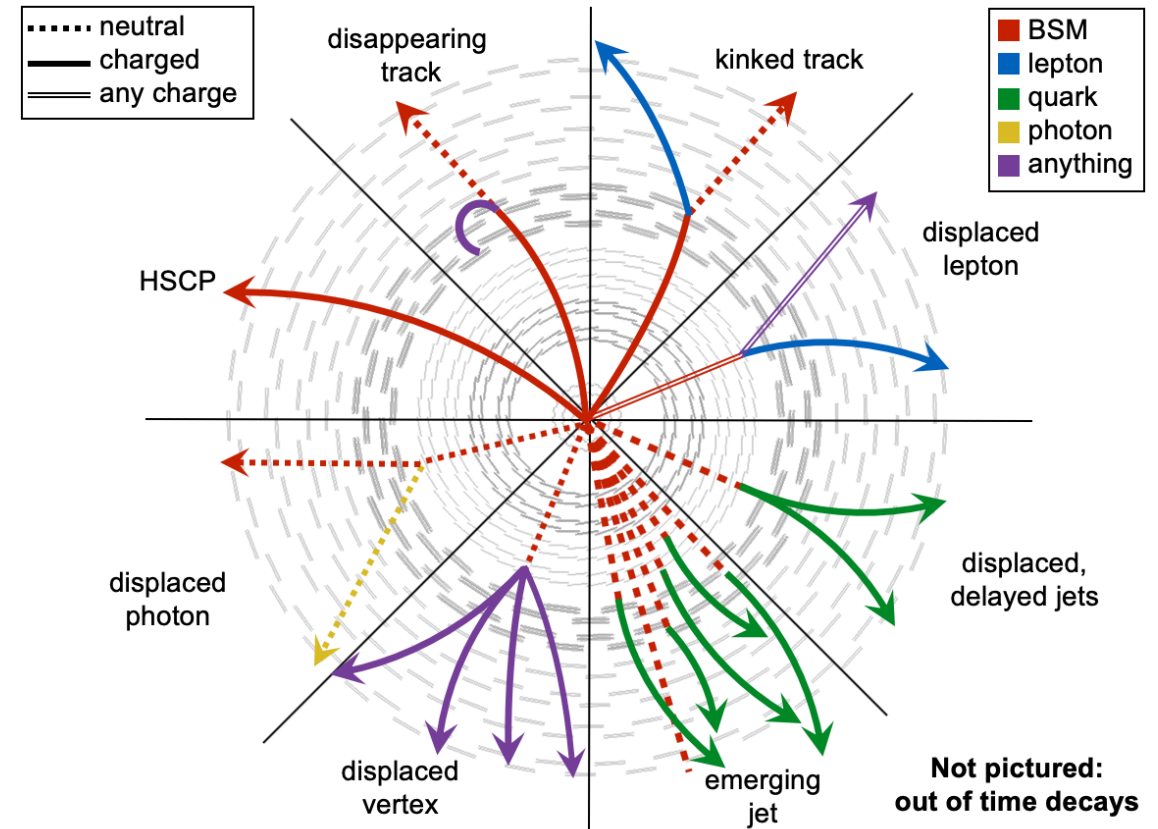
LLPs generically appear in many **BSM scenarios**

(SUSY, heavy neutral leptons, dark photons, inelastic dark matter, etc.)

**Great discovery potential!**

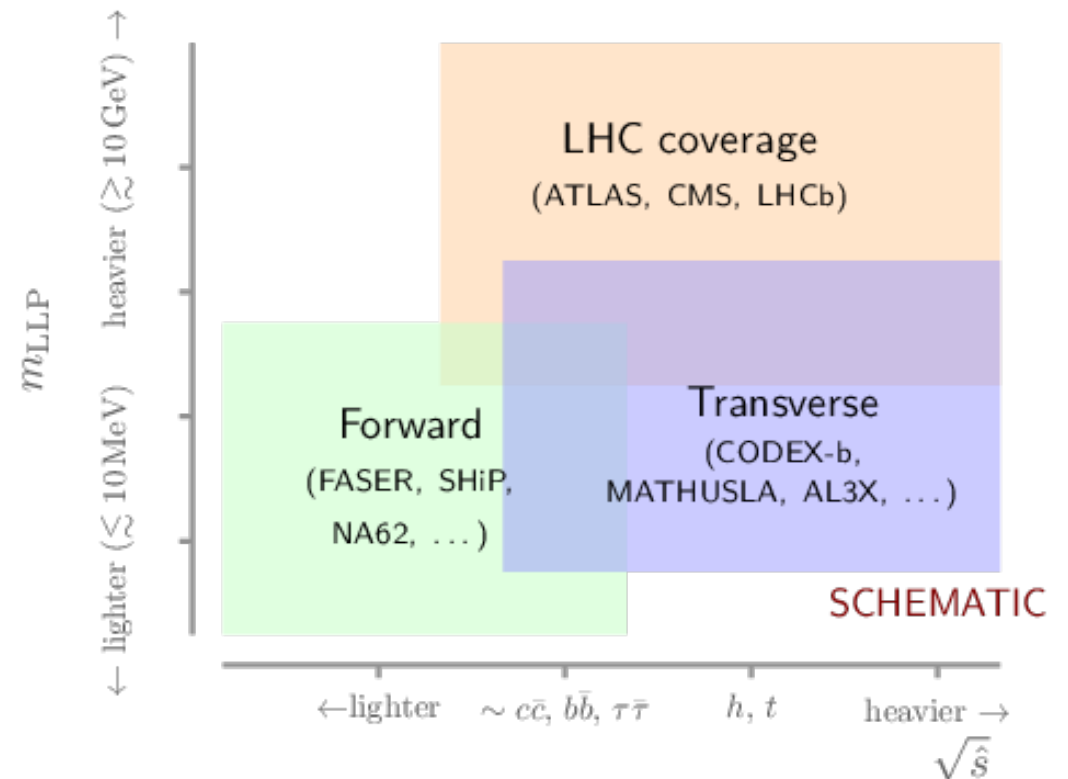
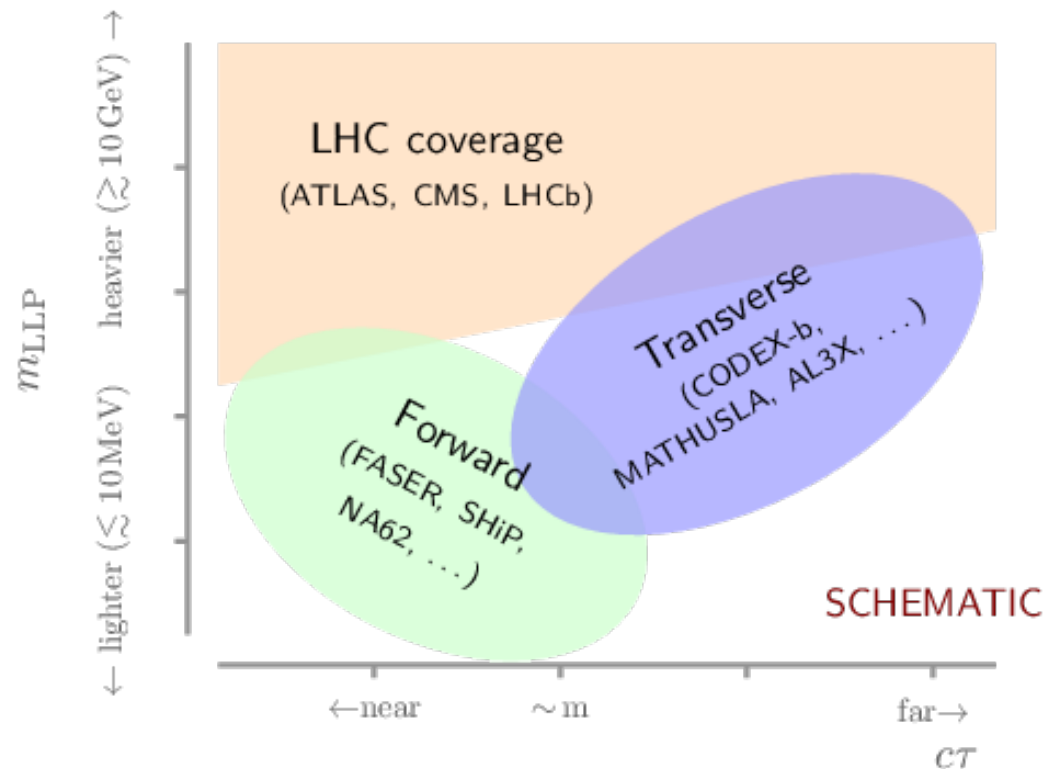
# LLP Searches at ATLAS, CMS, LHCb

- Many searches at the **general-purpose LHC detectors** have been done, are underway, and are planned (also for HL-LHC)
- However, **challenging**: not really designed for LLPs
  - Dedicated triggers
  - Unique offline object reconstruction
  - Atypical backgrounds
- Big opportunity to do something different with **dedicated experiments!**



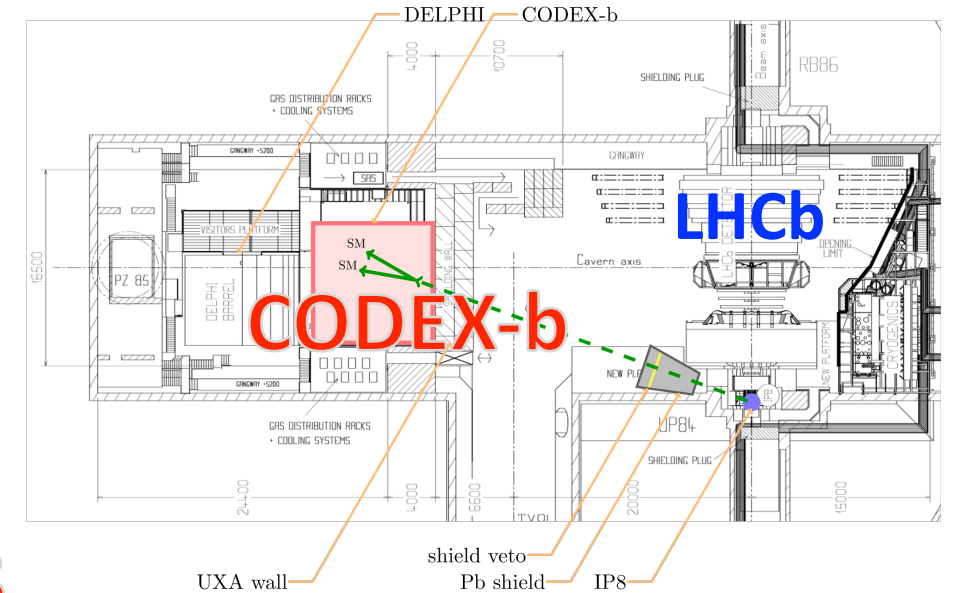
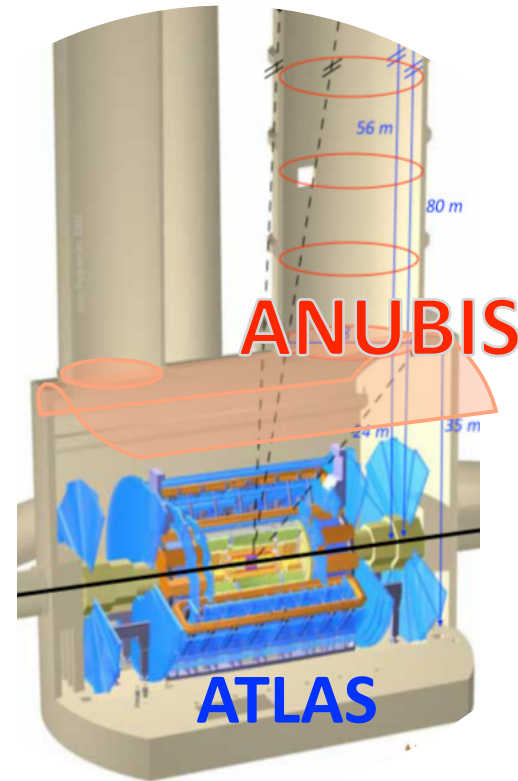
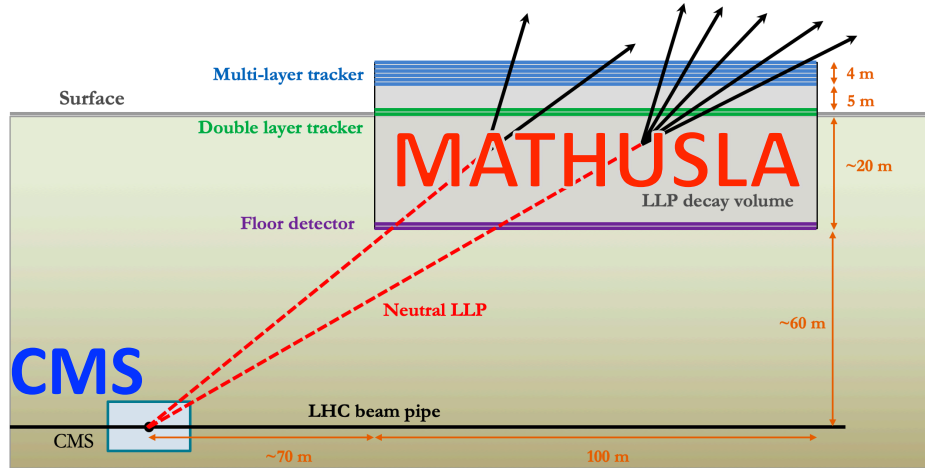
# Transverse Detectors at the HL-LHC

Transverse detectors like ANUBIS, CODEX-b, and MATHUSLA are sensitive to **uncovered regions of LLP phase space**



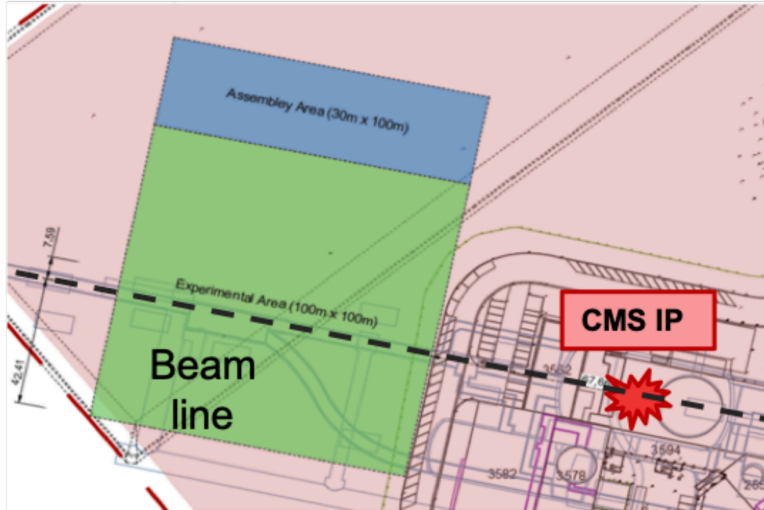
# ANUBIS, CODEX-b, and MATHUSLA

**Shielded tracking volumes** off-axis to the beam, and aligned with the **main LHC detectors**

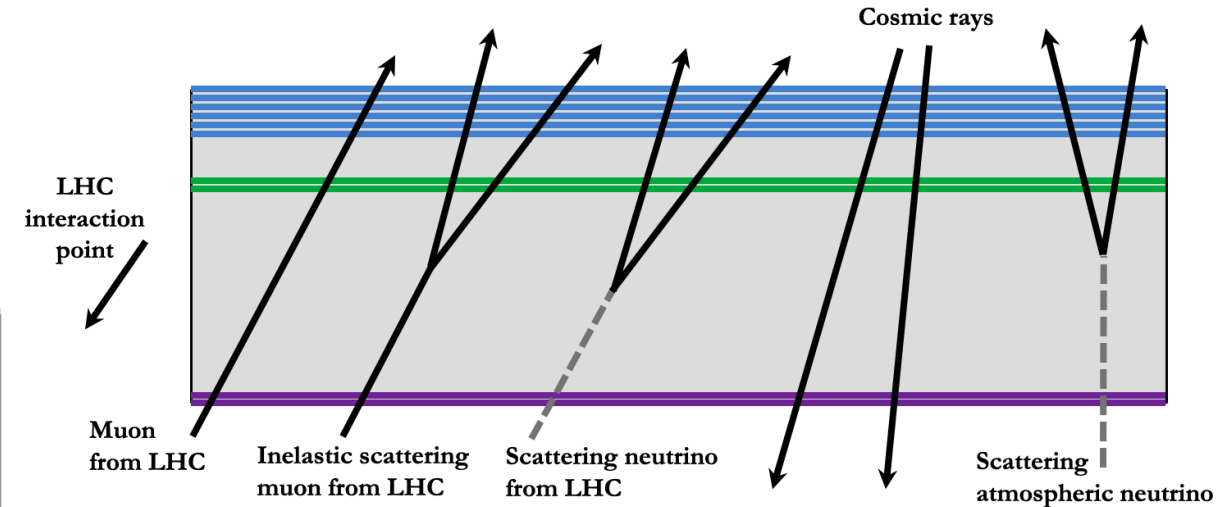
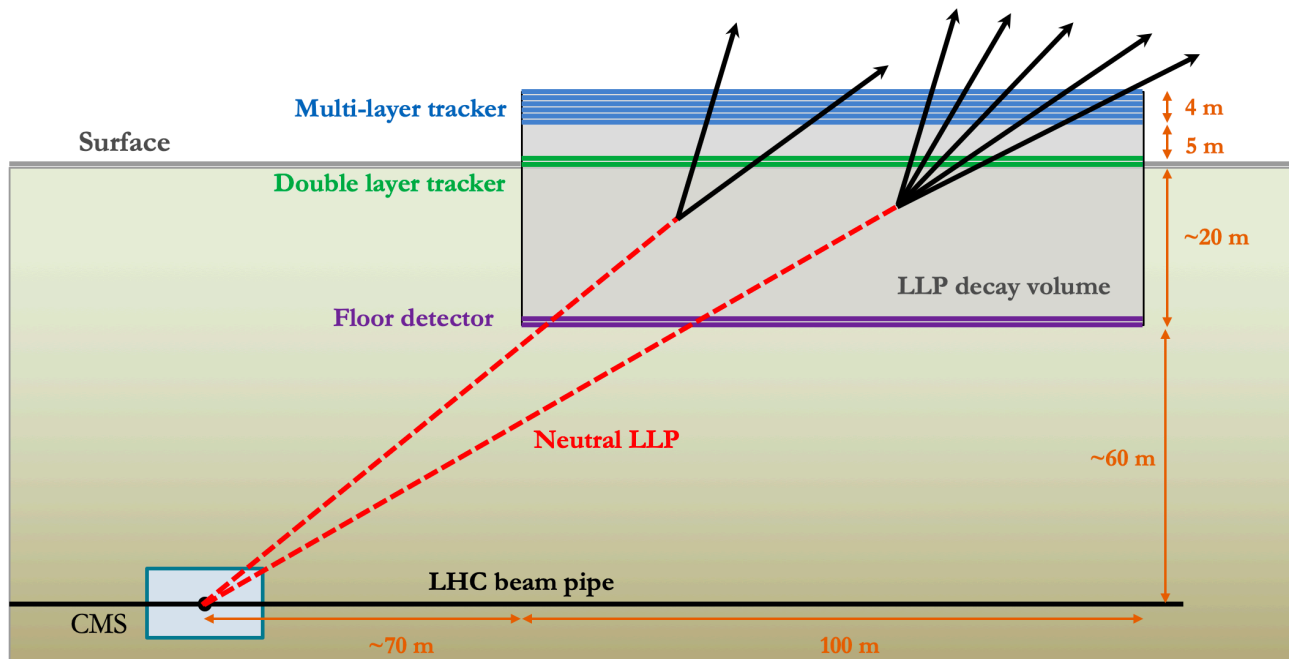


# MATHUSLA

## MAssive Timing Hodoscope for Ultra Stable neutral pArticles



- Large area (100m x 100m x 25m decay volume) surface detector located above **CMS**
- Extruded scintillators + SiPMs
- Cosmic  $\mu$  (1.7 MHz) and LHC  $\mu$  (10 Hz) rejected with **timing**



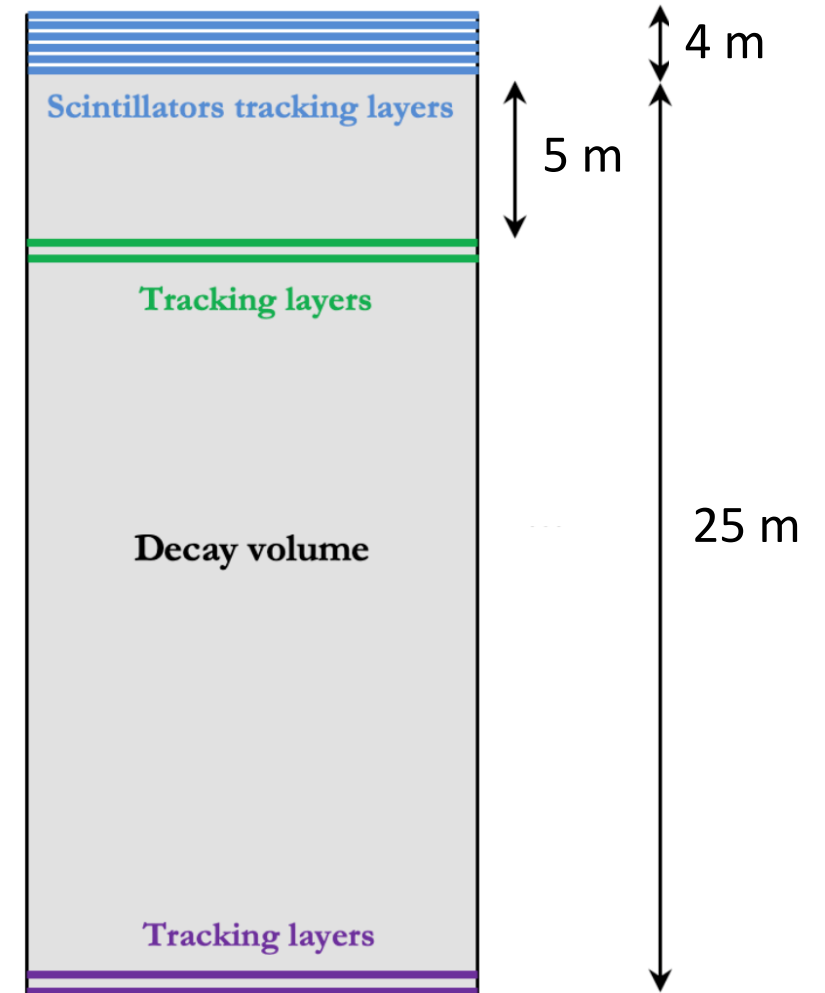
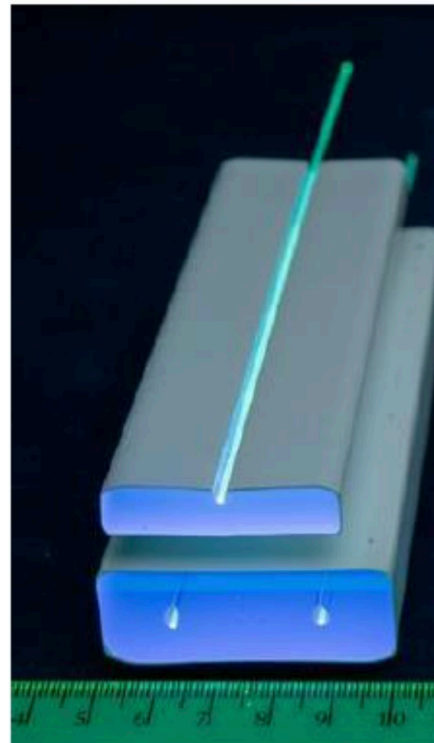
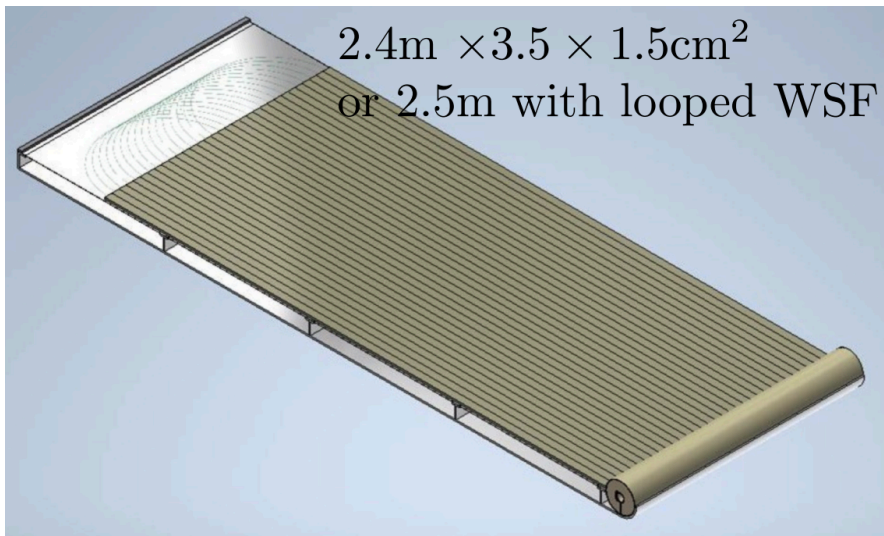
- [Public webpage](#)
- [Proposal \(arXiv:1606.06298\)](#)
- [Updated LOI \(arXiv:2009.01593\)](#)
- [Snowmass paper \(arXiv:2203.08126\)](#)



# MATHUSLA Detector Technology

- **Extruded scintillator bars with wavelength shifting fibers** read out by **silicon photomultipliers (SiPMs)**
- Transverse resolution of 1cm
- $\delta t$  between ends  $\rightarrow$  longitudinal resolution of 15cm

Six tracking layers on top. Two middle layers. Two floor layers.



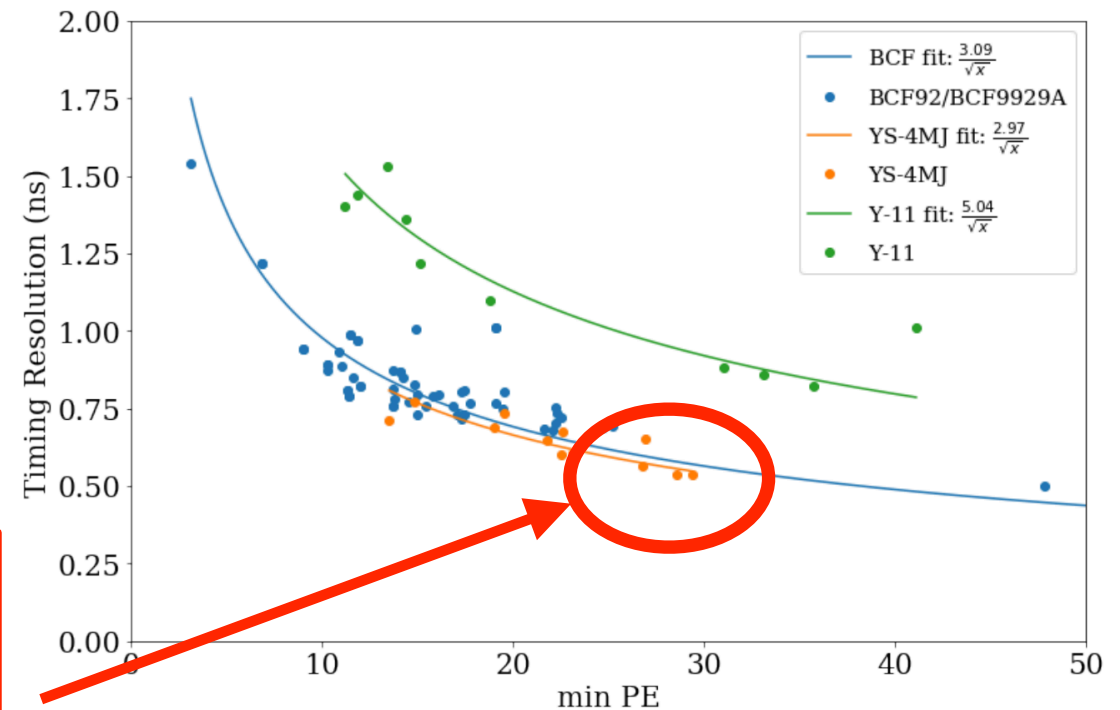
# Scintillator Timing Resolution

- Timing considerations:
  - Need to separate downwards from upwards going tracks
  - Need to reject low beta particles from neutrino QIS
- Therefore **need ~1 ns resolution** with **> 15 photoelectrons** per hit

Timing resolution of **0.54 ns** with worst light yield of **29 PE** well within MATHUSLA requirement

## Timing measurements

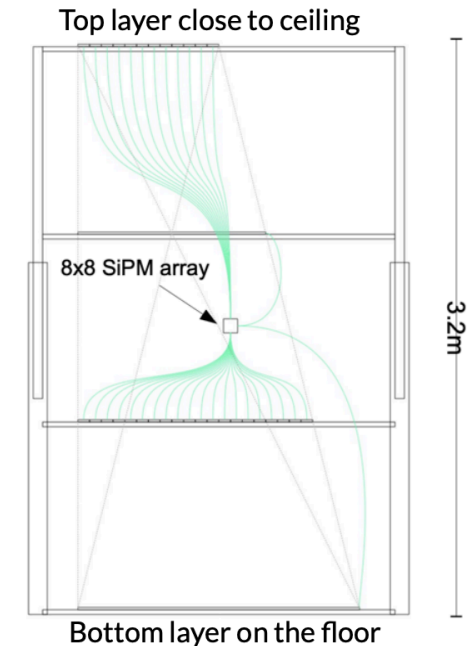
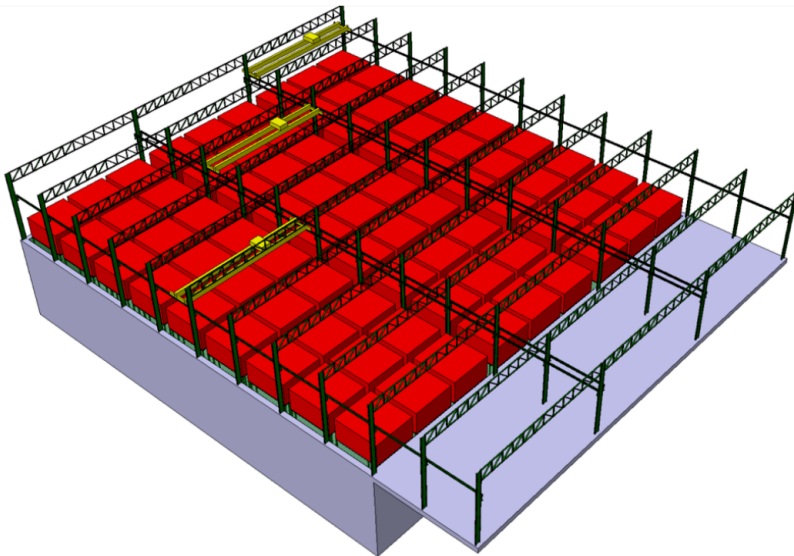
for a 5 m long fiber through a  $1 \times 4 \text{ cm}^2$  extrusion located at the center of the fiber





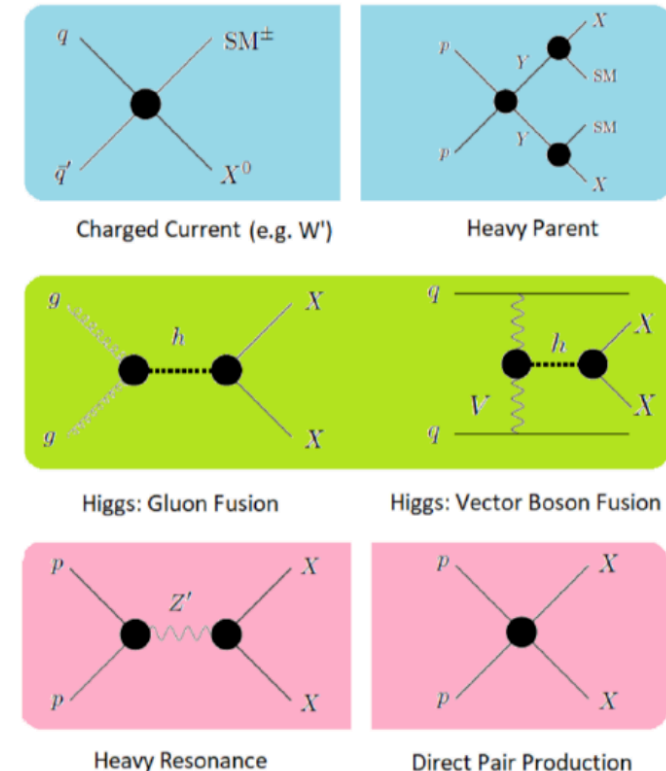
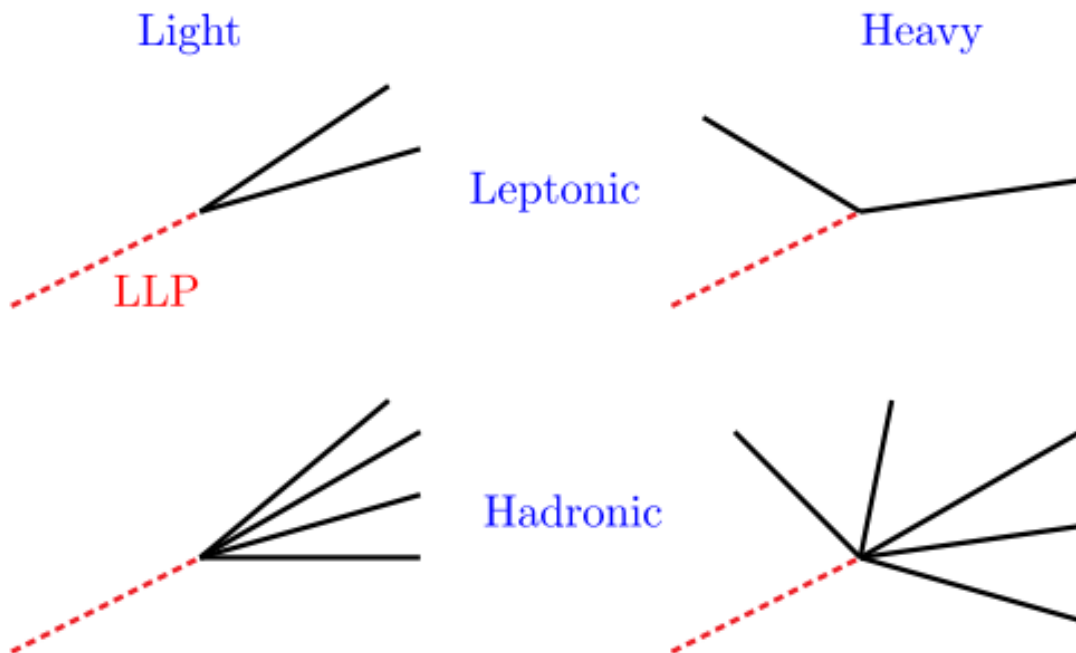
# MATHUSLA Detector Layout and Plans

- **Modular design** for staged assembly
- 100 modules in 100 m × 100 m footprint
  - Each module has 10 planes and 4 detector units per plane
- Investigating **RPC layers** for **cosmic ray studies**, up to PeV scale
  - Linear response for higher hit rates from extensive air showers
- Constructing **detector unit prototype** at the University of Victoria (64 channels, 4 layers)
  - **Goals:** replicate MATHUSLA tracking environment for resolution and efficiency studies, and validation of simulation
- **Conceptual Design Report** in preparation



# Identifying LLPs with MATHUSLA

- MATHUSLA can't measure particle momentum or energy, but:
- The track geometry can point to decay particle nature and LLP boost ([arXiv:1705.06327](https://arxiv.org/abs/1705.06327))
- Also studying incorporating MATHUSLA into CMS L1 trigger
- Could correlate event info offline and identify the LLP production mode

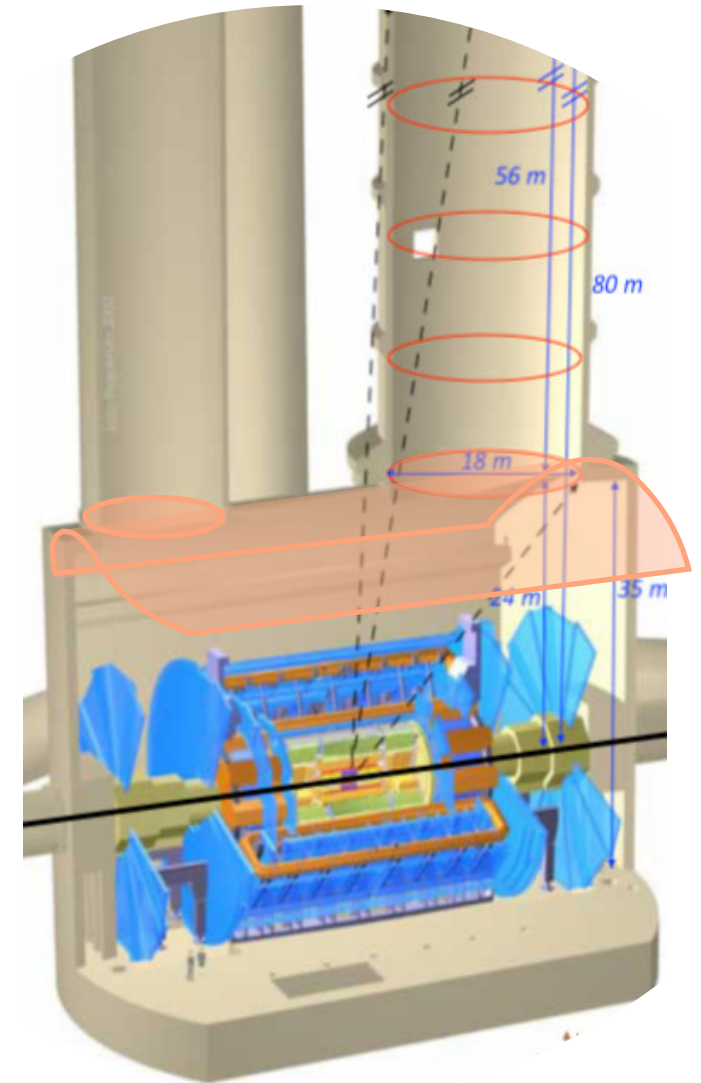
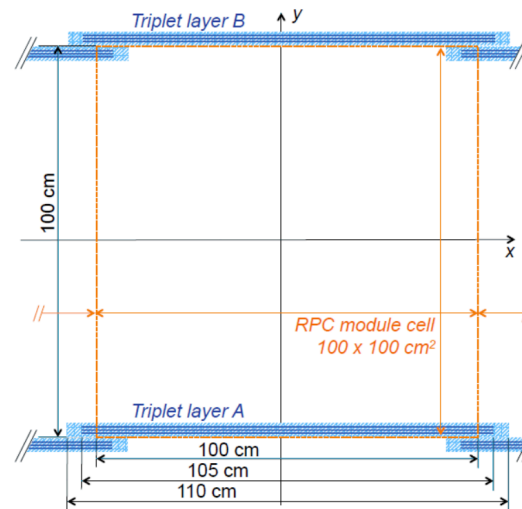


# ANUBIS

## AN Underground Belayed In-Shaft Experiment

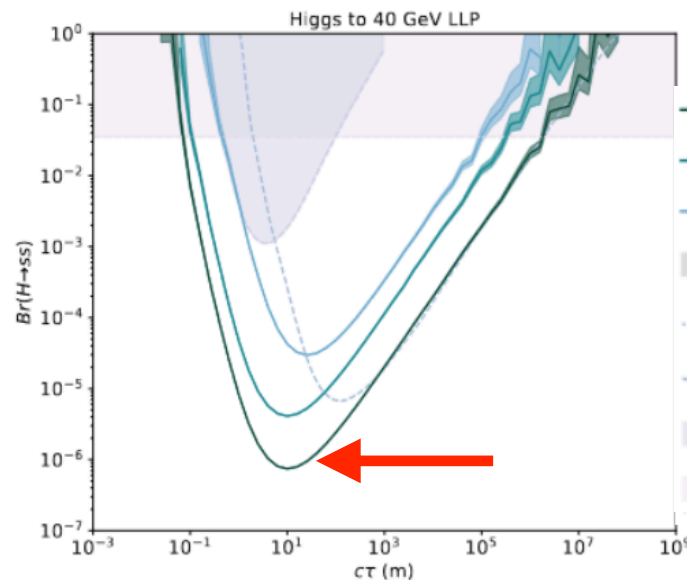
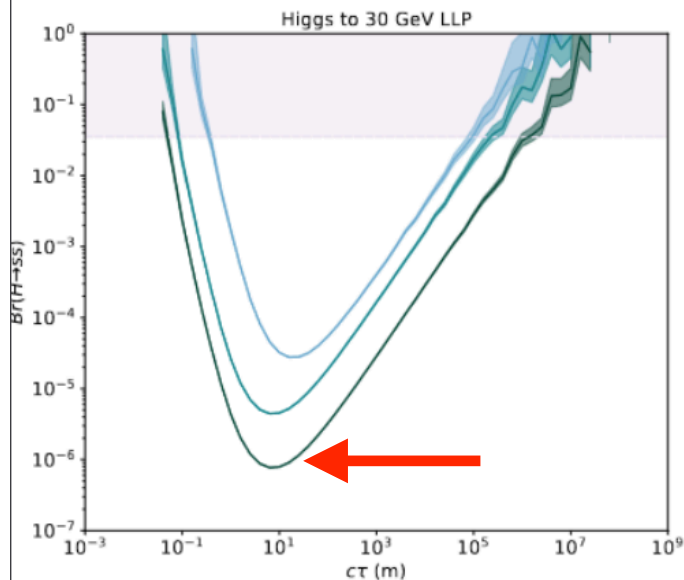
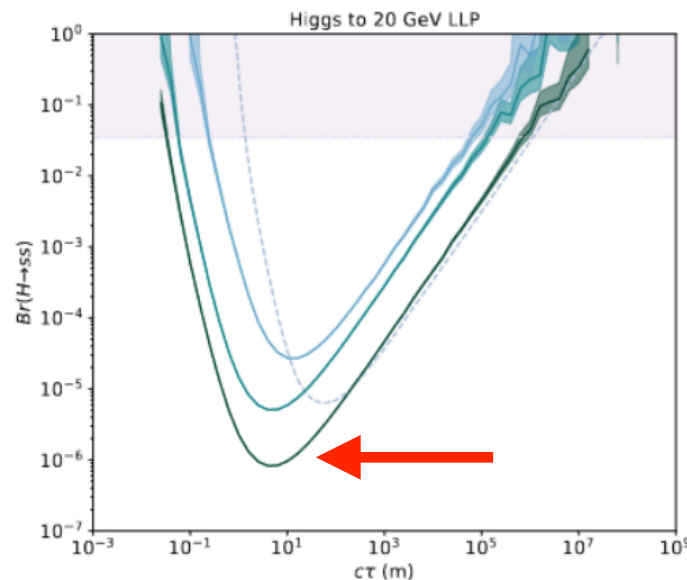
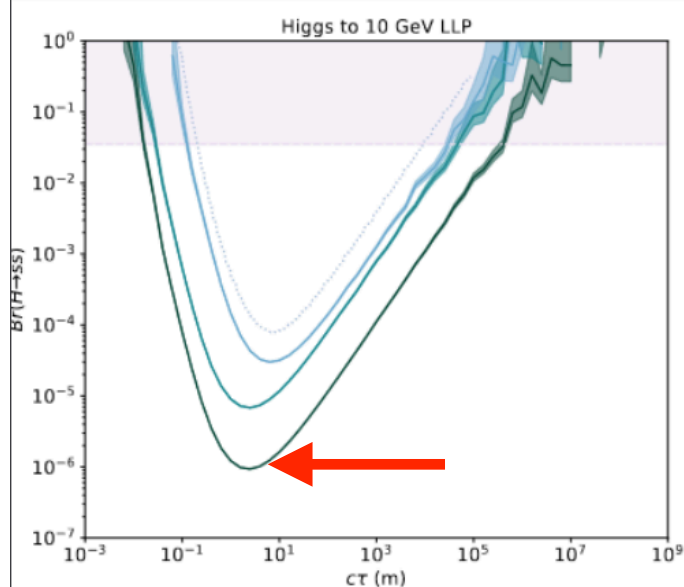
- Instrument ATLAS cavern ceiling and service shafts with **RPC tracking stations**
  - Recently converged on ceiling + shaft geometry
  - Larger active volume:  $4.3 \times 10^4 \text{m}^3$
  - Larger total detector area:  $\mathcal{O}(10^3 \text{m}^2)$
- ATLAS subdetectors serve as active + passive veto
- Participate in ATLAS L1 trigger decision

Detector element:  
two RPC triplets

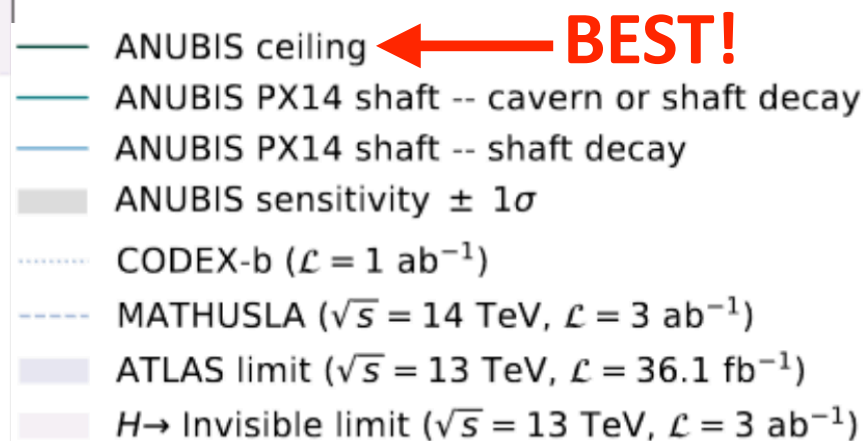


- [Public webpage](#)
- [Proposal \(arXiv:1909.13022\)](#)

# ANUBIS Projected Sensitivity



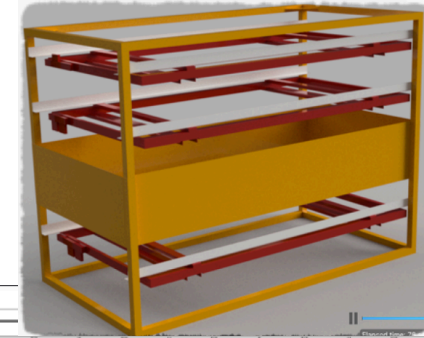
- **NEW!** Updated  $H \rightarrow ss \rightarrow 4b$  sensitivity
- Signal estimates from particle-level (non-G4) simulation
- Assume no background and search for 4 signal events
- **Ceiling geometry has the best sensitivity**, so converged on this choice



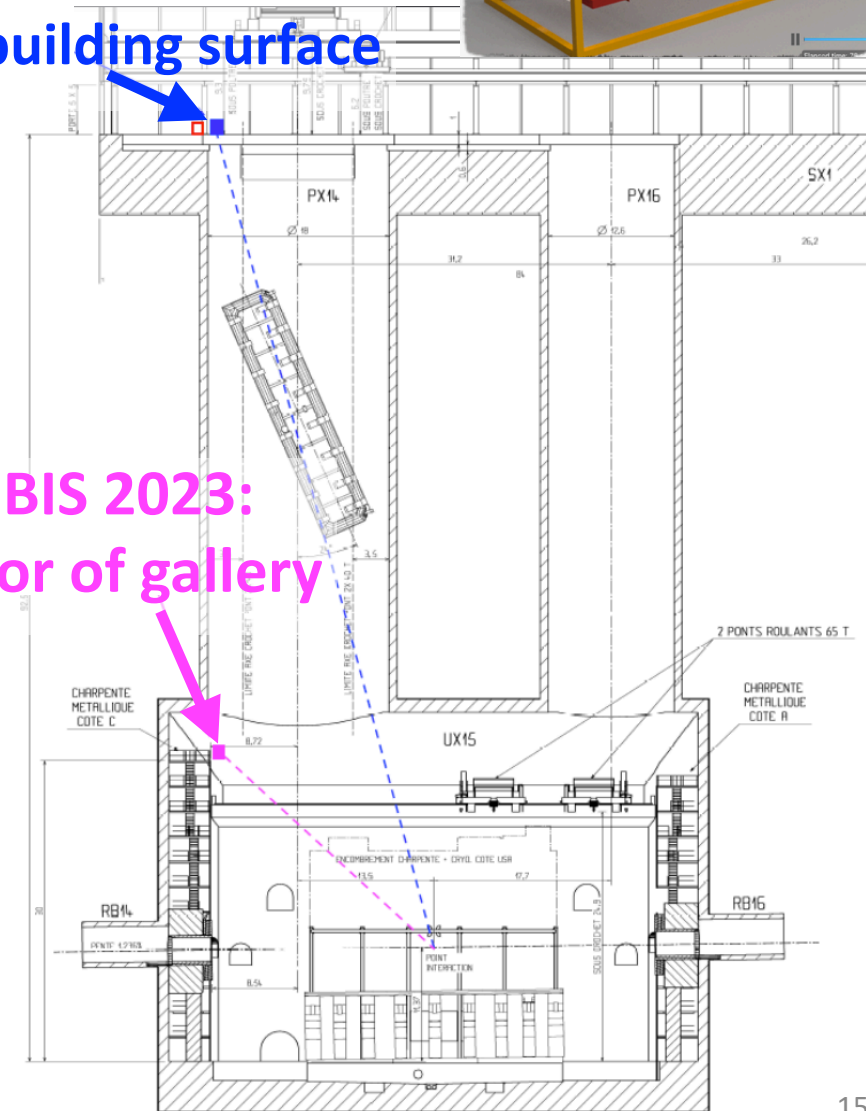
# proANUBIS

- **proANUBIS will be a prototype detector** (1.8m x 1 m x 1 m) installed during Run 3
- Formed from 6 BIS7 RPC singlets
- **Performance goals:**
  - Commissioning, perform hit + track efficiency measurements
  - Test track extrapolation from ATLAS
    - Use single muon trigger to identify muons and synchronize ATLAS and proANUBIS
- **Physics goals:**
  - **Validate GEANT4 simulation**
  - Measure rates of secondaries from hadrons interacting with the concrete lid (2022)
  - Measure rates of hadrons from punch-through jets (2023)

**proANUBIS 2022:**  
**SX1 building surface**

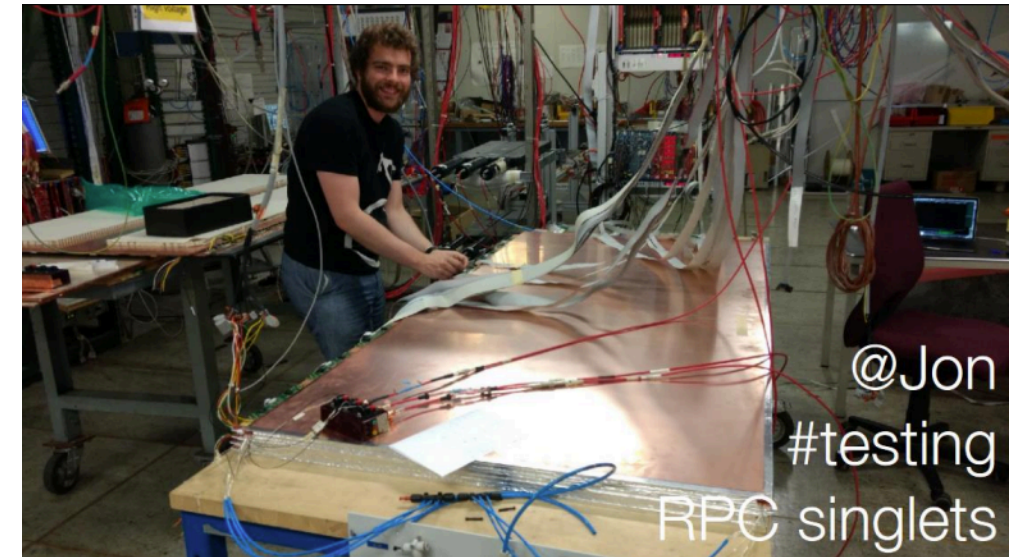


**proANUBIS 2023:**  
**12th floor of gallery**

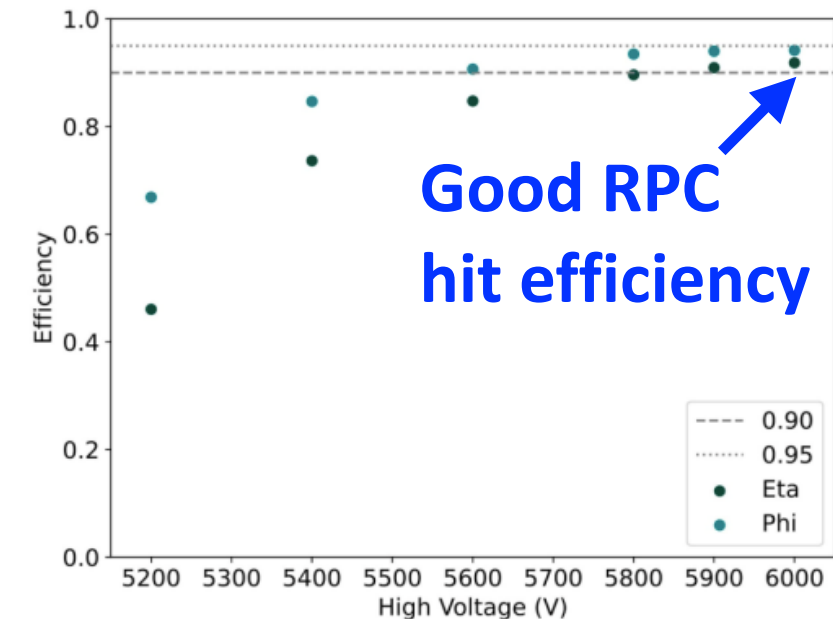
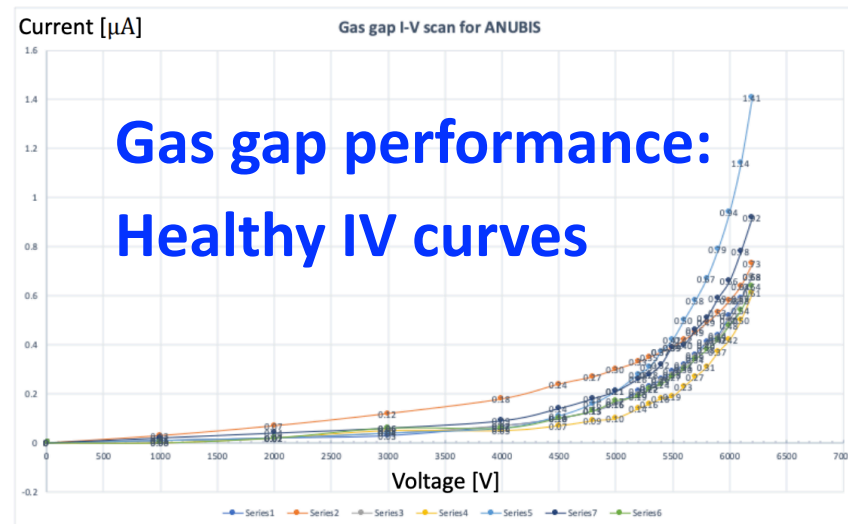
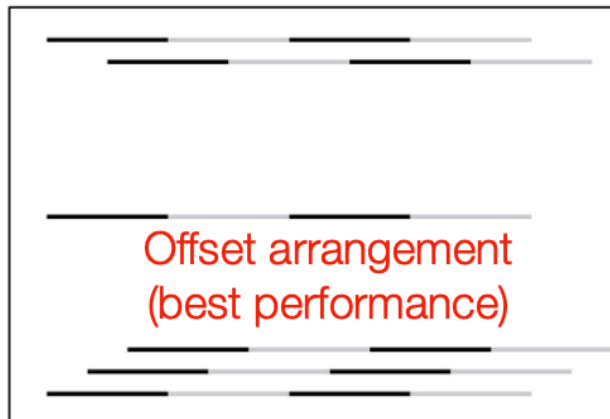




# proANUBIS Assembly and First Performance

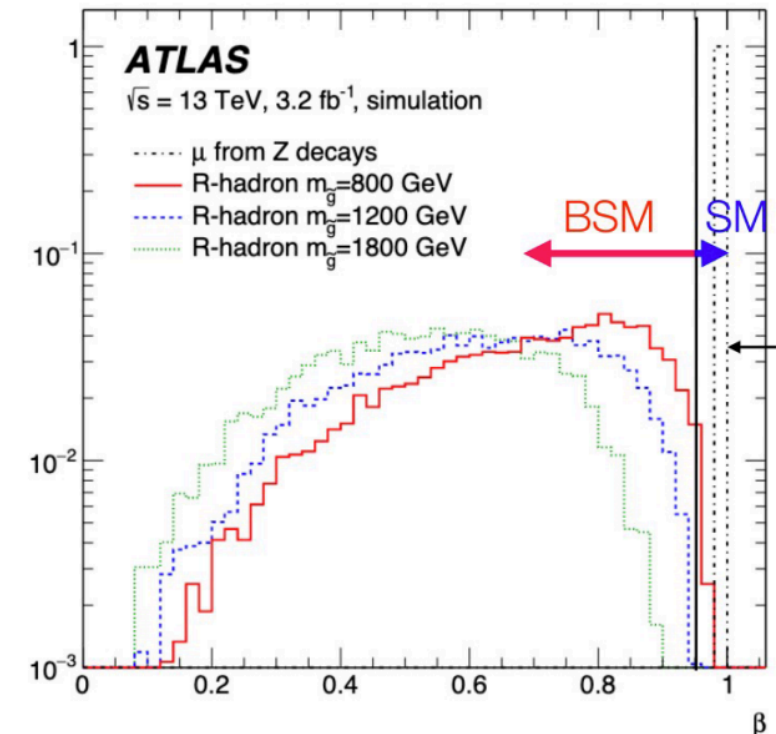
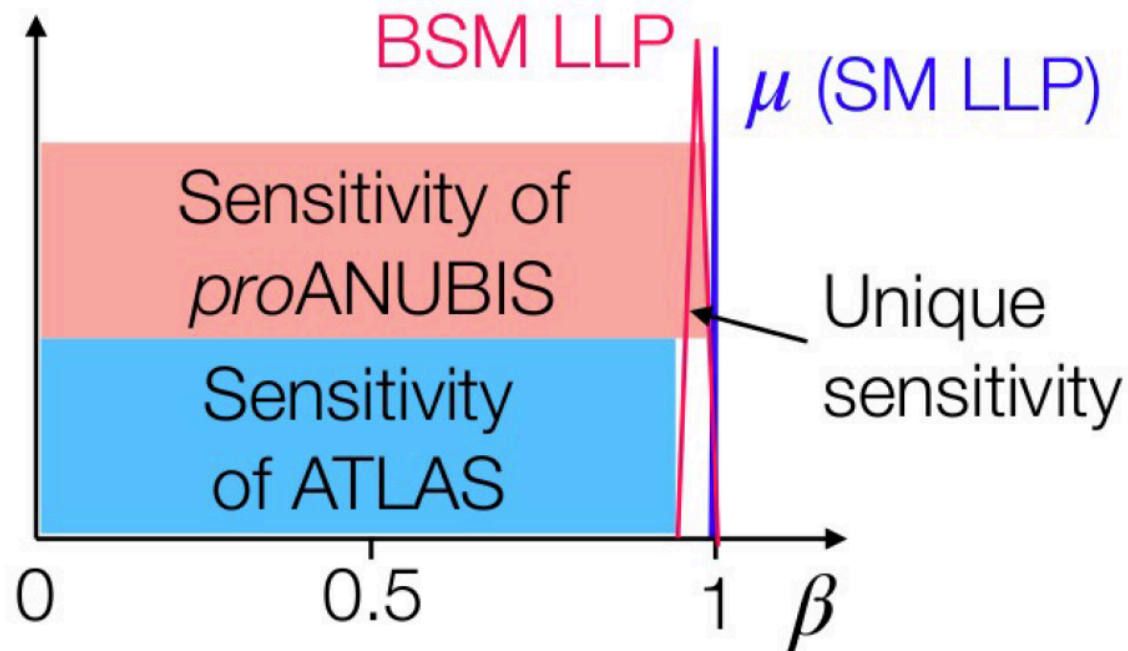


## Three tracking layers



# Unique Sensitivity Already for ProANUBIS

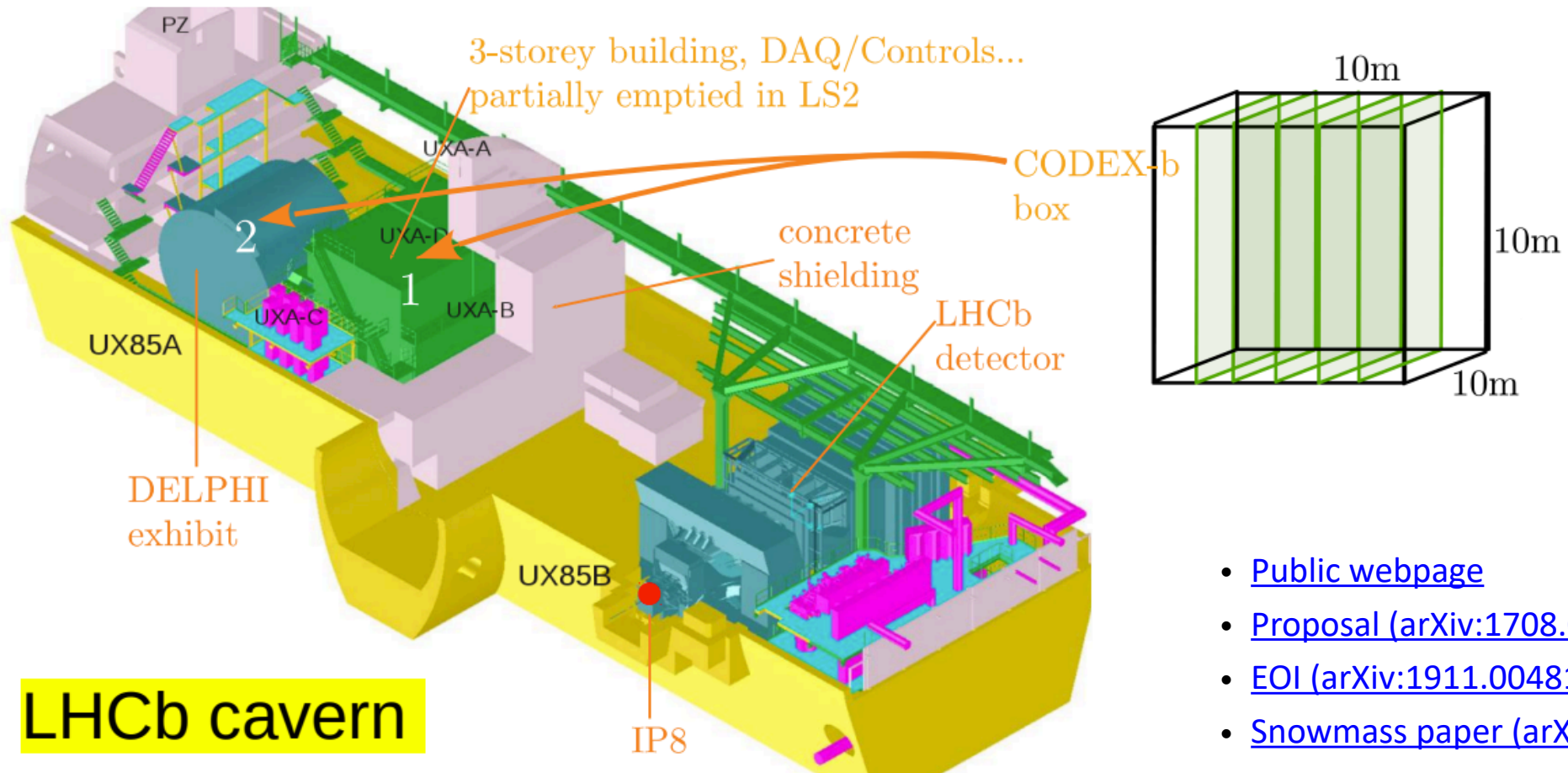
- Large time-of-flight and great timing resolution ( $\sim 300$  ps)
- Superb  $\beta = v/c$  resolution:  $\delta_\beta \sim 0.1\%$ 
  - ATLAS has  $\delta_\beta \sim 2\text{-}3\%$
- Therefore **unique sensitivity** to charged massive particles with  $\beta$  near 1
- Maybe could shed some light on ATLAS excess in dE/dx search ([arXiv:2205.06013](https://arxiv.org/abs/2205.06013))?



# CODEX-b

## COmpact D etector for EXotics at LHCb

- 10m x 10m x 10m box of **RPC** tracking layers
- Behind existing 3.2m thick **shield**
- **Transverse** to LHCb
- Located in **counting room (1)** or **DELPHI exhibit (2)** ?
  - Several locations being studied
- **Integration** with LHCb triggerless DAQ

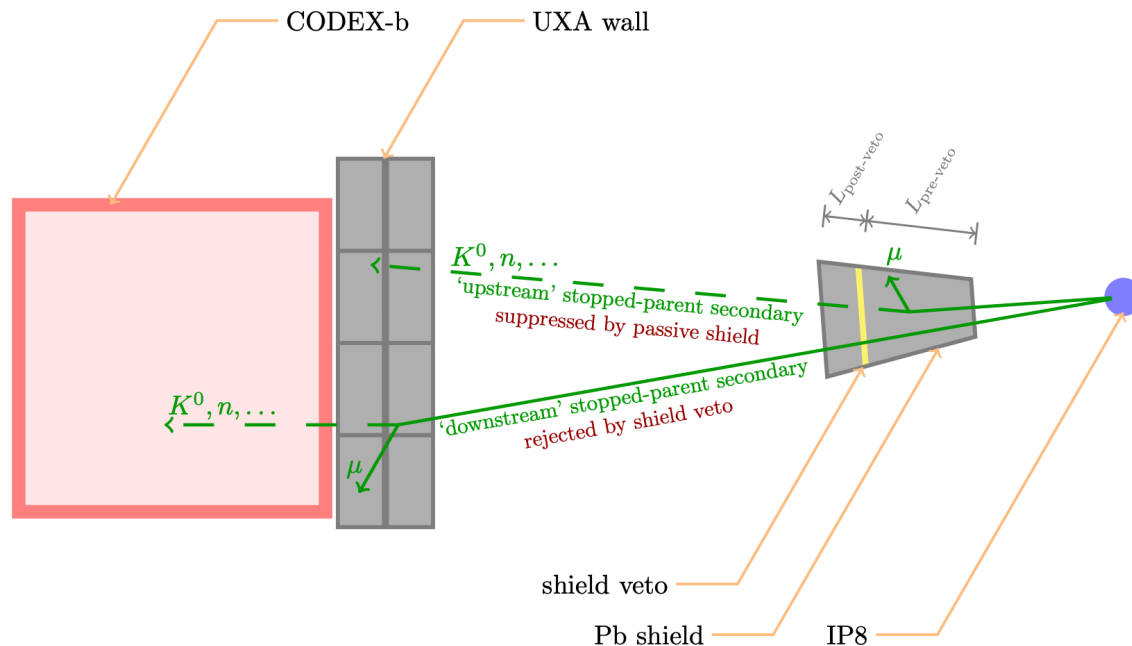


- [Public webpage](#)
- [Proposal \(arXiv:1708.09395\)](#)
- [EOI \(arXiv:1911.00481\)](#)
- [Snowmass paper \(arXiv:2203.07316\)](#)



# Backgrounds in CODEX-b

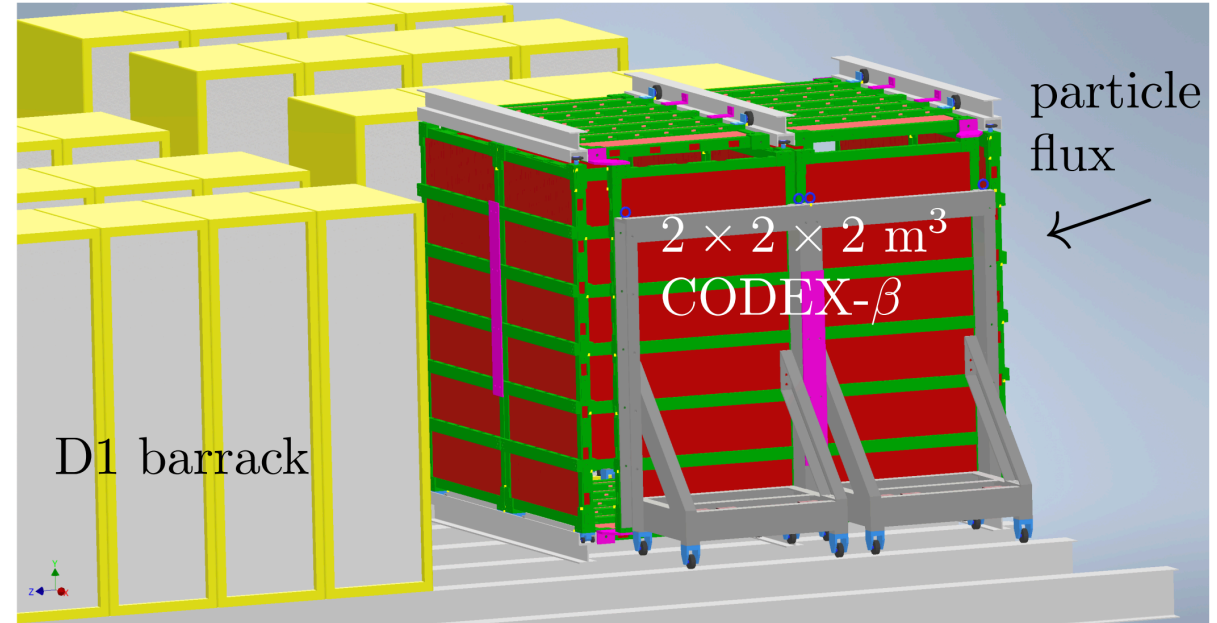
- **Main backgrounds:**
  - $\mu$  (primary or secondary) that can penetrate concrete+Pb shield
  - $n/\pi^\pm/K^\pm/K_L^0$
- **Additional potential sources:**
  - LHC machine-induced, Thermal neutrons, Neutrinos



- **Detailed bkg simulation:**
  - [arXiv:1708.09395](https://arxiv.org/abs/1708.09395), [arXiv:1911.00481](https://arxiv.org/abs/1911.00481)
  - **Bkg levels reduced to  $< \mathcal{O}$  (1 event) in  $300 \text{ fb}^{-1}$  with shields + active/topological vetoes**
- Measured backgrounds in D1 area in 2018:
  - [arXiv:1912.03846](https://arxiv.org/abs/1912.03846)
- FLUKA campaign from CERN RP validated Pythia simulation

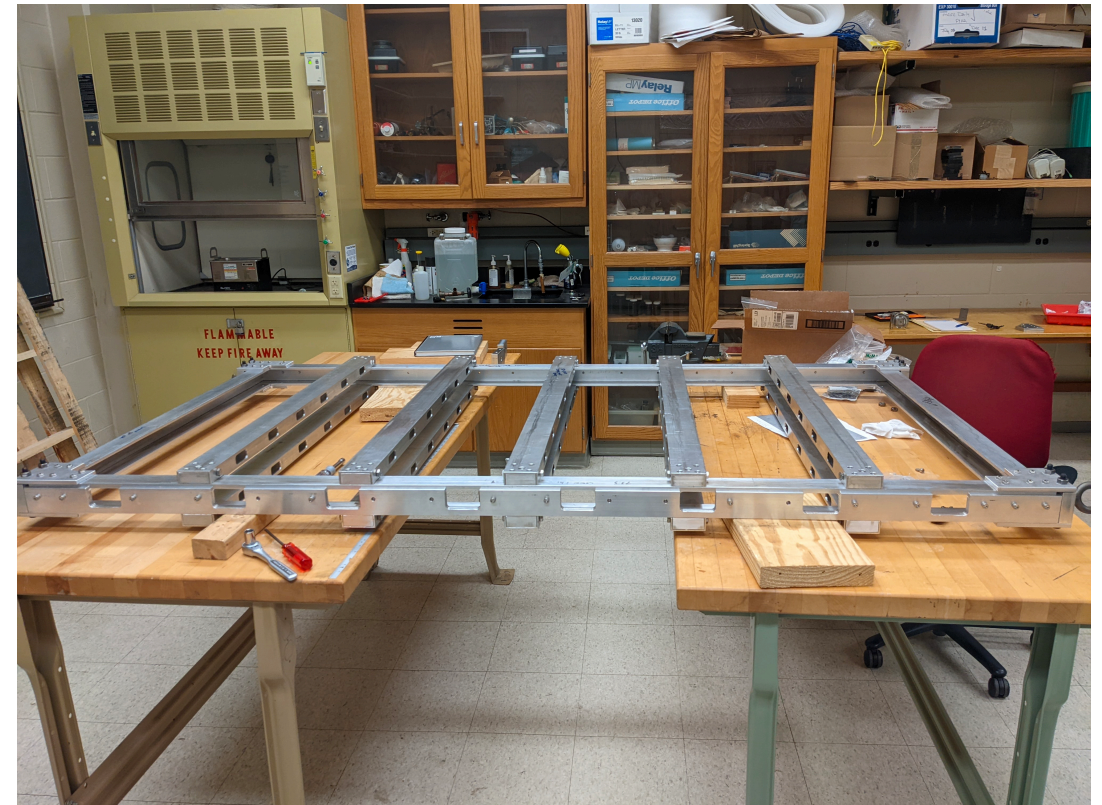
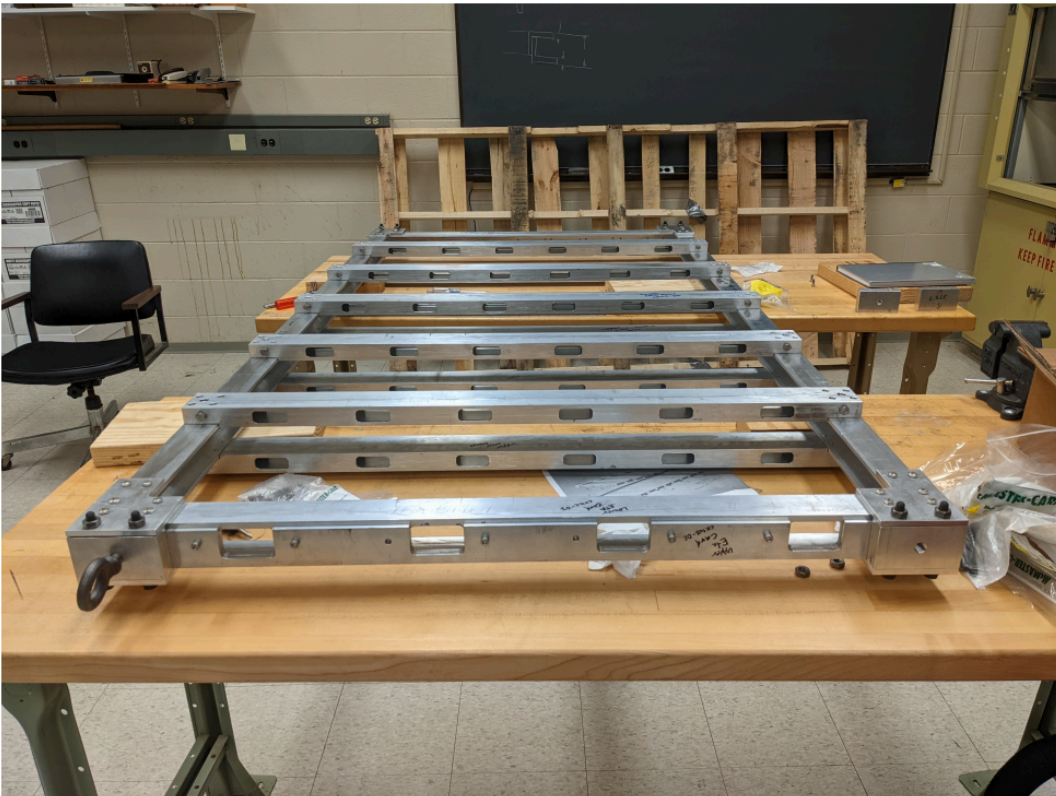
# CODEX- $\beta$

- **CODEX- $\beta$  will be a prototype detector**  
(2 m x 2 m x 2 m) installed during Run 3 in the D1 ground floor barrack space
- Formed from **14 BIS7 chambers**
  - Triplets on each face and one internal module
  - Funding secured!
- **Main goals:**
  - Integrate with LHCb online
  - Reconstruct  $K_L^0$  and measure bkg rates
  - Validate simulation



# CODEX CX1 Frame

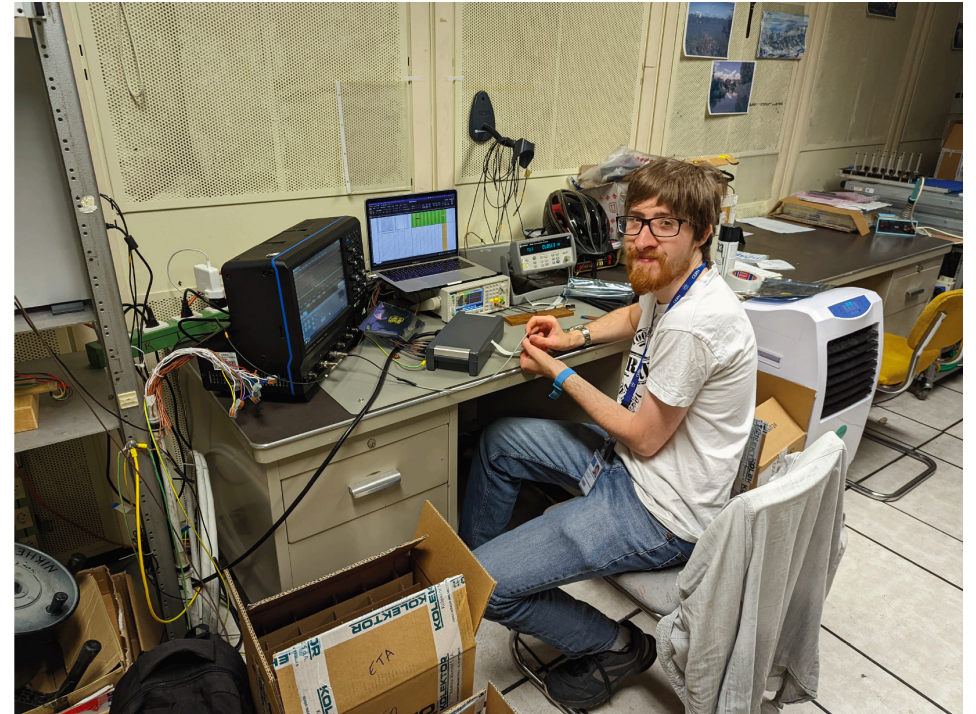
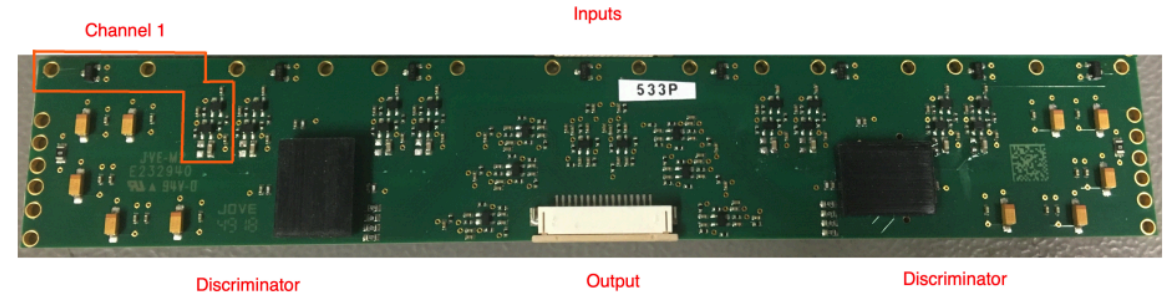
- Assembled new CX1 frame to hold one RPC triplet
  - Very precise: reduced change of RPC misalignment
  - Structural engineering report in preparation



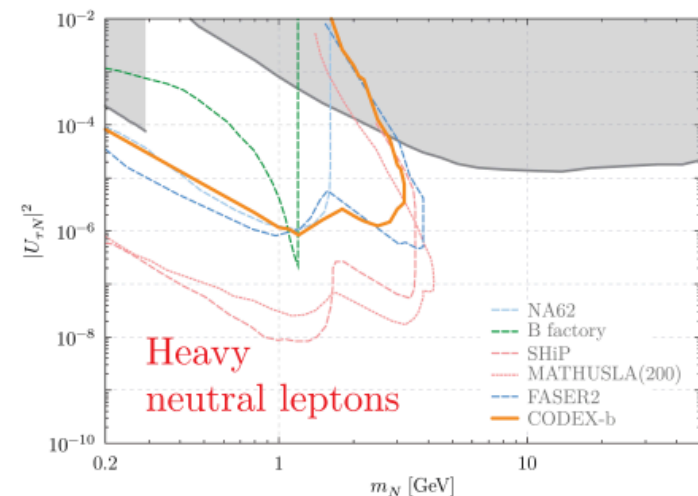
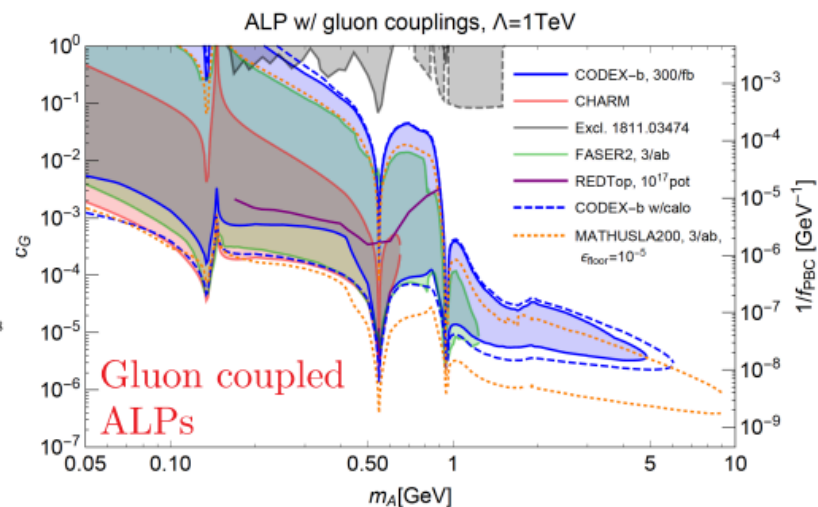
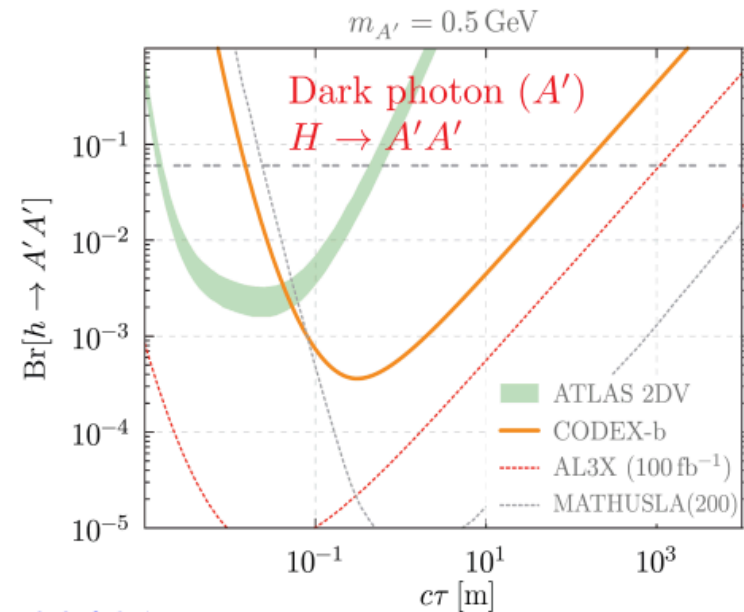
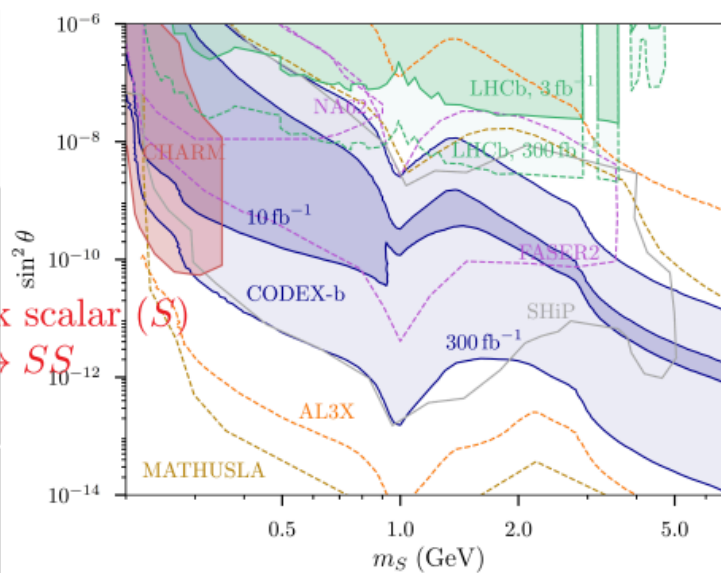
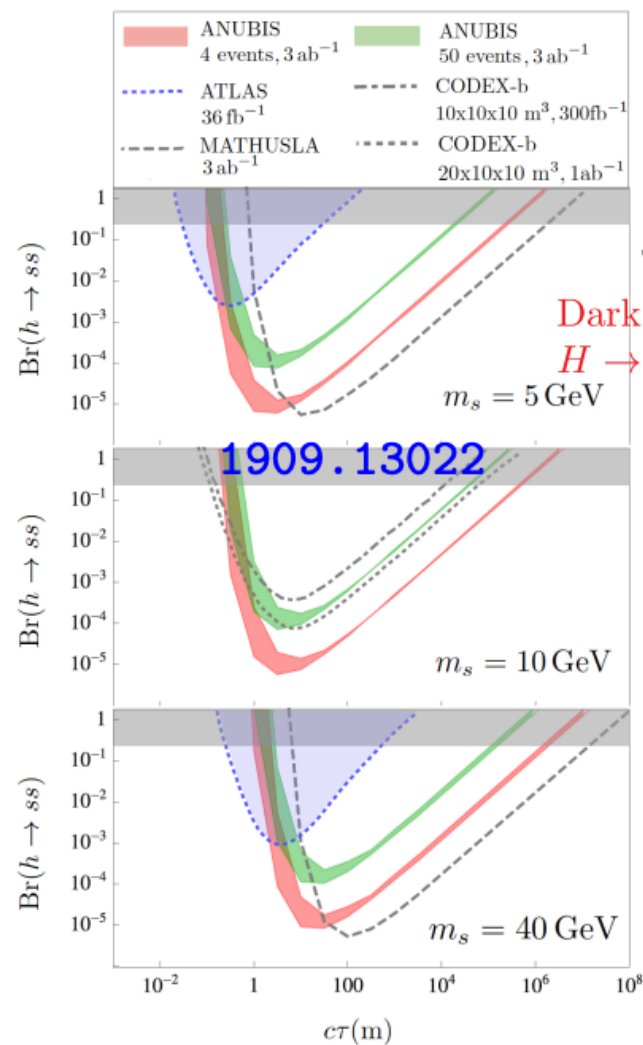


# CODEX RPC Assembly

- Currently procuring strip panels for RPC singlets
- Once singlets built, can assemble triplets, and mount to CX1 frame to form the full module
- Once one module built, full construction can occur
- **Tested quality assurance of 422 readout boards** over the summer
  - Documented in internal note
- **Chamber assembly** starting next year



# Transverse Detectors: Unique Sensitivity!



# Summary

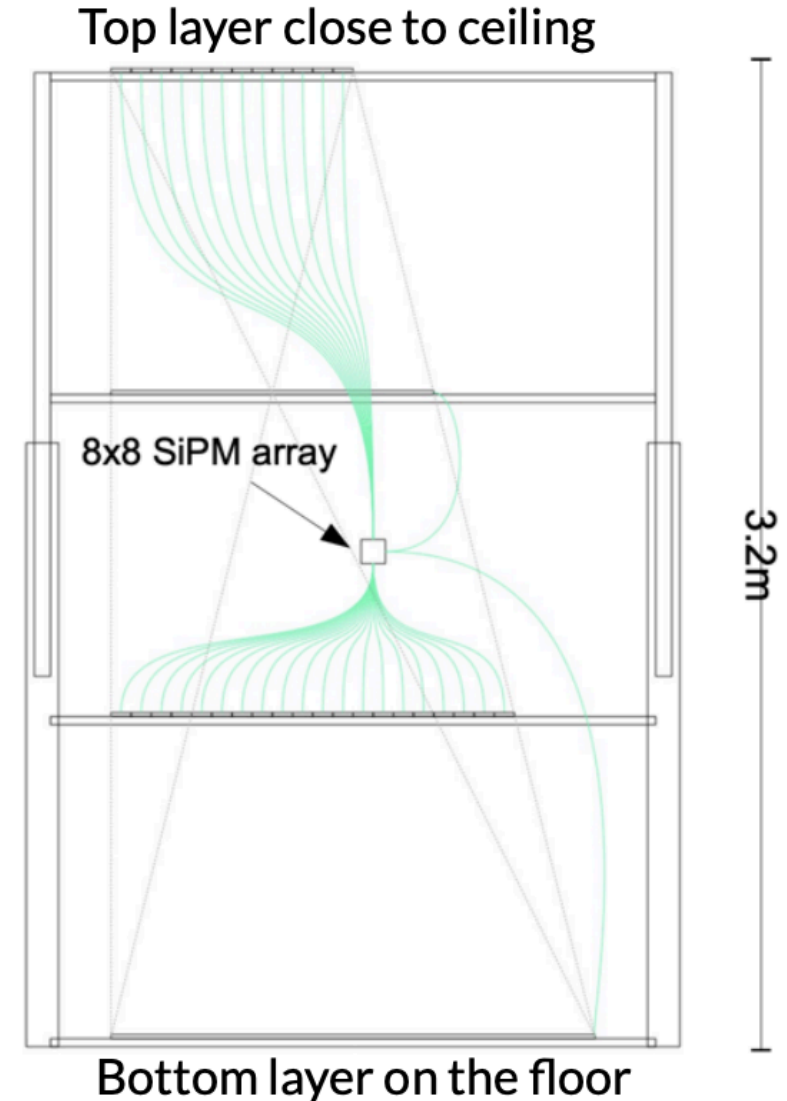
- Transverse experiments will probe unique LLP parameter space, beyond what is accessible with forward or beam dump experiments
- Let's make sure we don't miss new physics!
- Join us!



# Backup

# MATHUSLA Prototype

- A few year ago: had a small test stand above ATLAS to show the proof-of-principle
- **Now:** constructing **detector unit prototype** at the University of Victoria
  - 64 channels, 4 layers
- **Goals:**
  - Replicate MATHUSLA tracking environment for resolution and efficiency studies with cosmic muons
  - Provide validation of simulation





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