Long-Lived Particles in MATHUSLA

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Standard Model of Particle Physics

- The Standard Model (SM) is currently the best model of the Universe's building blocks
- All observable matter explained by SM particles
- Remarkably accurate
  - Predicted many phenomena
  - 2012 discovery of the Higgs Boson

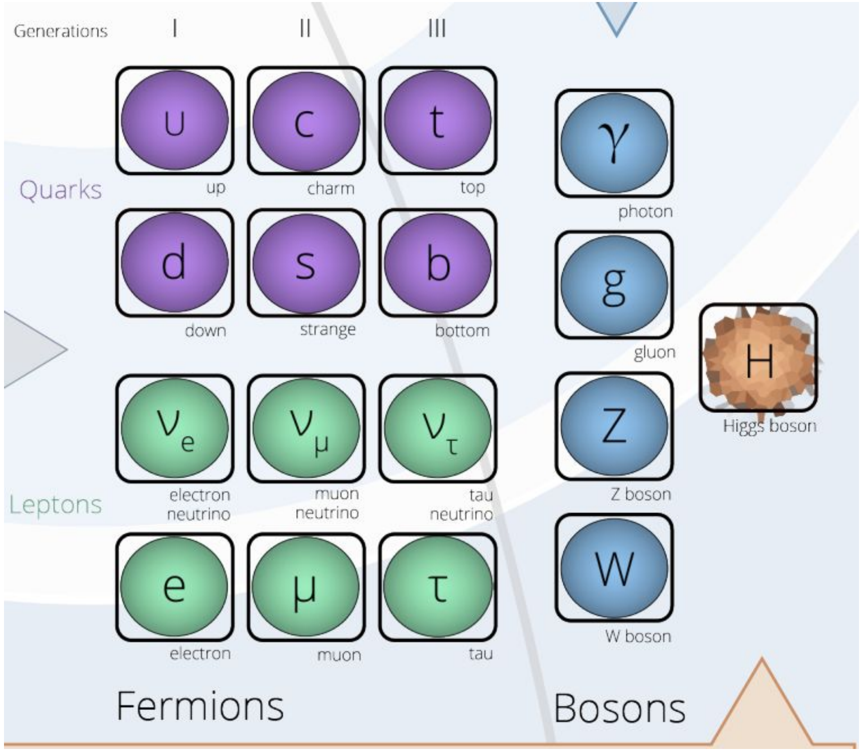

Figure 1: Table of standard model particles and force mediators from [1]

Limitations of the Standard Model

- As great as the SM is, it cannot explain everything

- Dark Matter (DM) makes up about 23% of the Universe's total mass [2], but never been directly observed
  - Stars and gases rotating in spiral galaxies
  - Cosmic microwave background (CMB) radiation

- Electroweak Hierarchy Problem
  - Higgs Boson is not as heavy as theory predictions [3]

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Long-Lived Particles in Beyond Standard Model Physics

- Beyond Standard Model (BSM) theories for unanswered questions
  - How to discover new physics? … Searching for new particles!

- Long-lived particles (LLPs) are particles with long lifetimes
  - Some examples in the SM are muons, pions and neutrons
  - Long lifetimes can arise from several possibilities

- LLPs are actually quite common in BSM theories
  - Some DM models predict DM particles with long lifetimes

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Searches for LLPs

- Large Hadron Collider (LHC) is largest and most powerful particle accelerator [4]

- LLP experiments at the LHC
  - ATLAS and CMS detectors for LLP signal detection

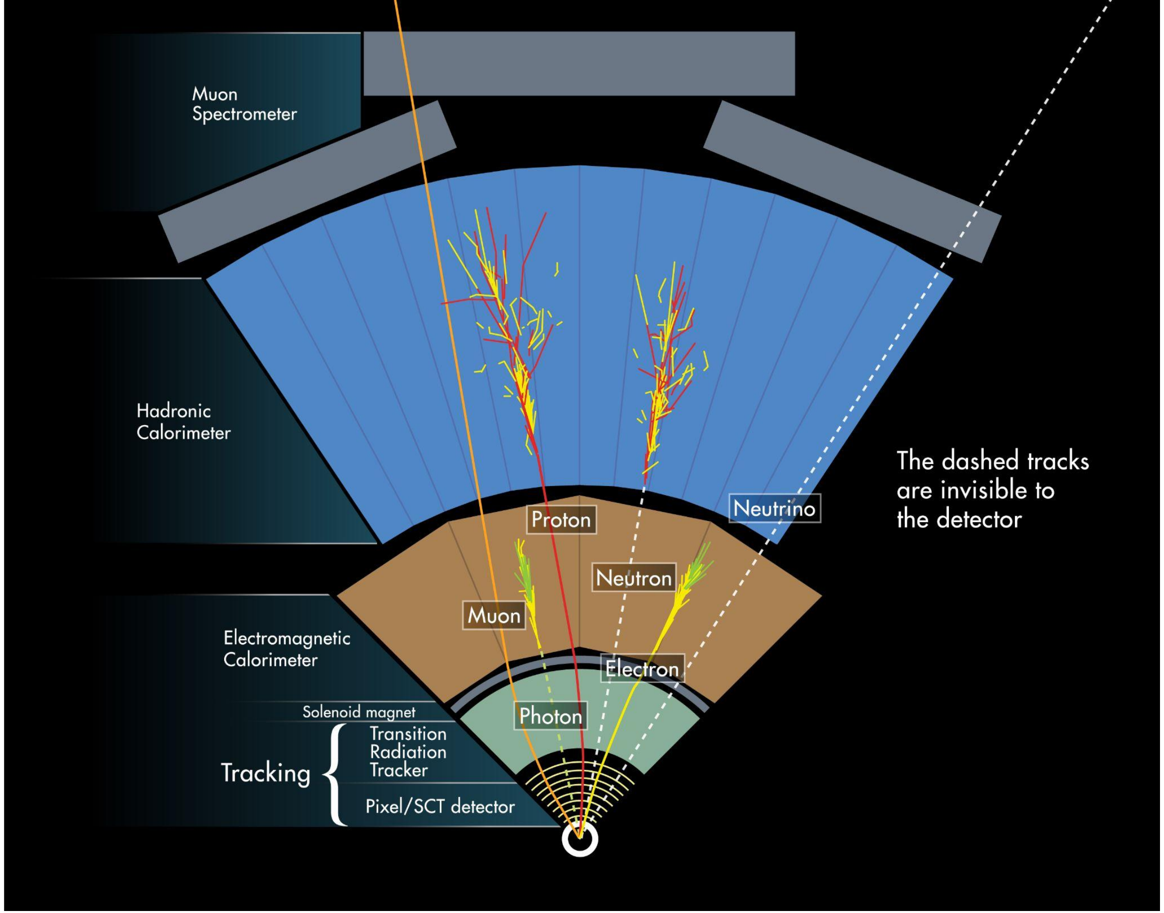

Figure 2: Cross-section of a sector of the ATLAS detector with select particle signatures [5]

Why is MATHUSLA needed?

- MATHUSLA (Massive Timing Hodoscope for Ultra Stable neutraL pArticles) is proposed detector for LLPs
- MATHUSLA to start in ~2025
- ATLAS and CMS detectors are limited by their size
- Excellent background signal rejection
- Limited searches for neutral LLPs

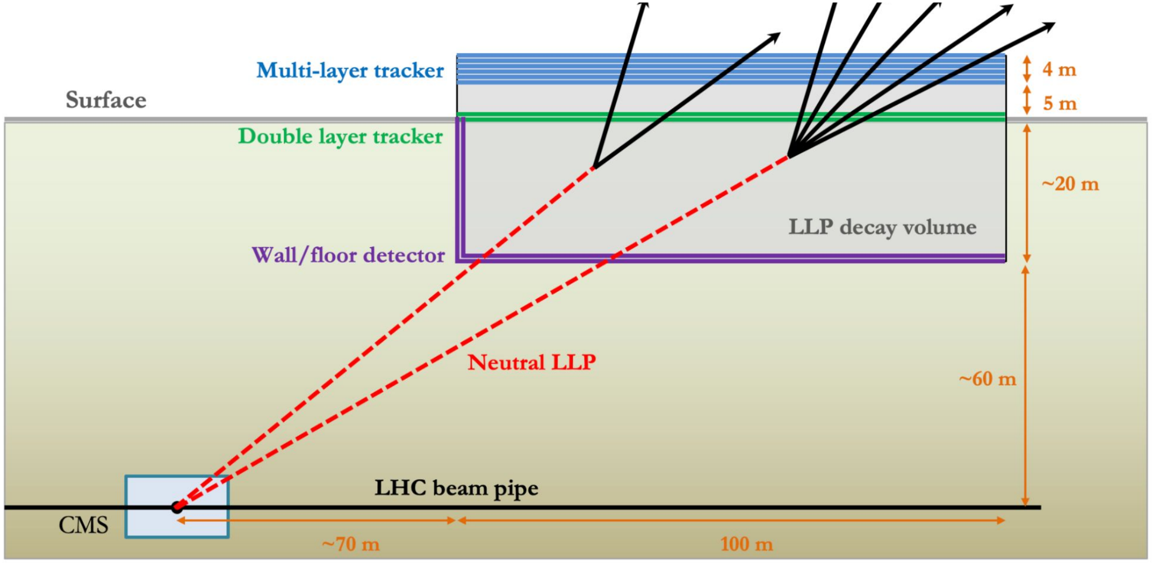

Figure 3: Proposed MATHUSLA detector layout [6]

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MATHUSLA Detector Module

- Experimental area to cover an area of about 100 m x 100 m

- MATHUSLA to be built from individual detector modules
  - ~ 81 modules
  - 9 m x 9 m x 30 m
  - 10 layers

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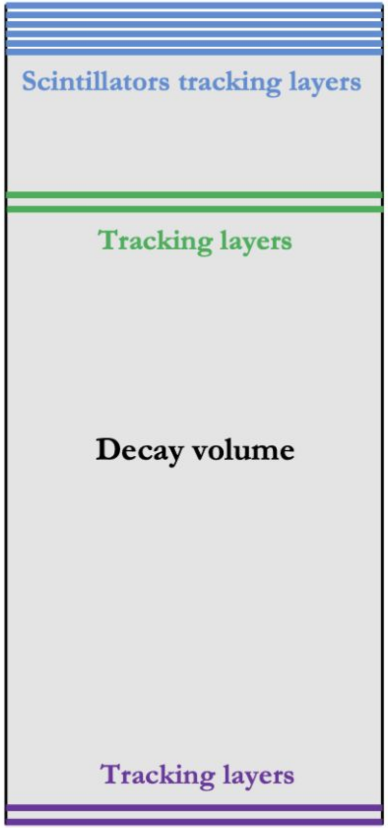

Figure 4: MATHUSLA detector module [6]

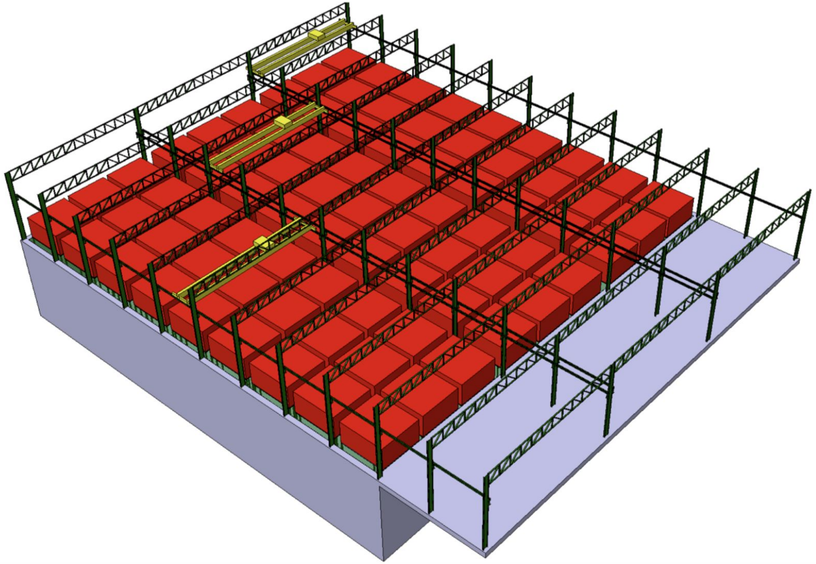

Figure 5: 3D rendering of the MATHUSLA detector. Red blocks show the individual detector modules [6]

Scintillator Tracking Layer

- Scintillating tracking layers for particle tracking
- Plastic scintillating bars
    - Reflective coating
- Wavelength shifting (WLS) fibres
- SiPMs coupled to WLS fibres on either end of bars
- Nanosecond resolution
- Many readout channels required

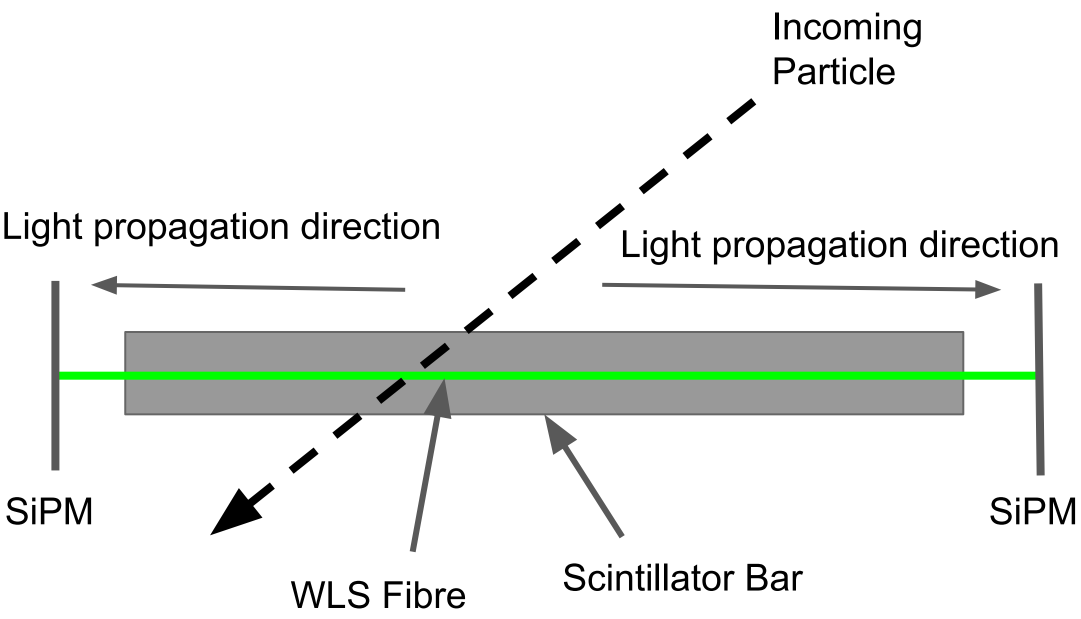

Figure 6: Simplified diagram of the scintillating layer tracking for time of flight measurements

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Thesis Project Objectives

1. Evaluate the performance of a commercial data acquisition system (CAEN DT5550W with an A55PETx PETIROC piggyback board) for nanosecond resolution time of flight measurements
    a. Address issues with signal noise
    b. Determine the ASIC channel failure rate
2. Design a small-scale prototype of the MATHUSLA detector module
    a. Module frame design
    b. Scintillating layer connectors
    c. Silicon photomultiplier (SiPM) holders

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Time of Flight Measurements and Noise Debugging

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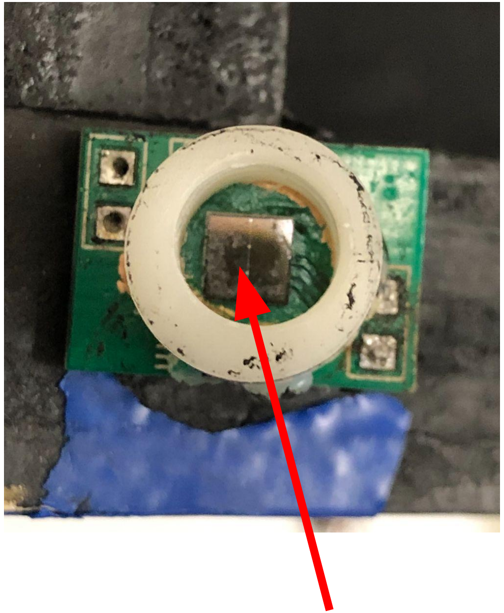
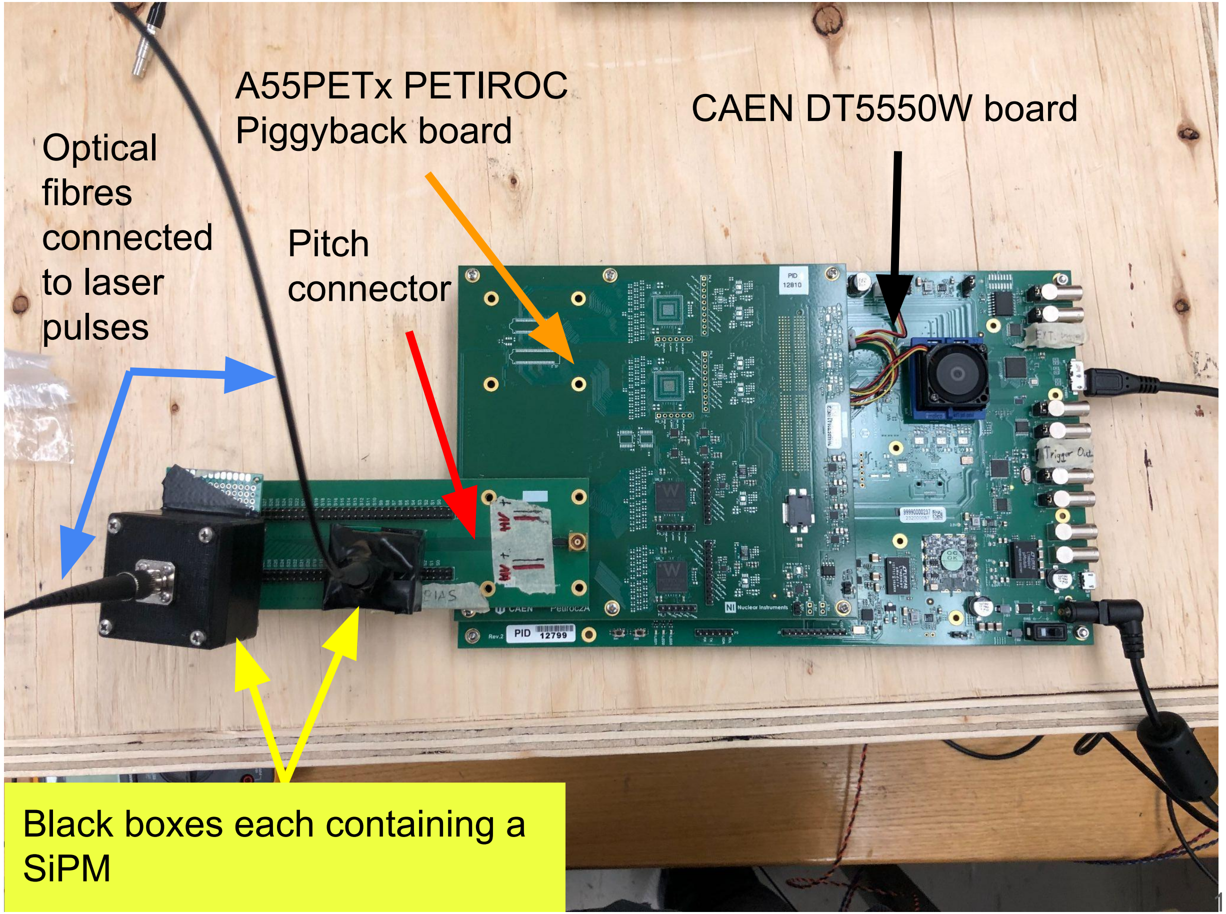
CAEN DT5550W Data Acquisition System



Silicon diode surface



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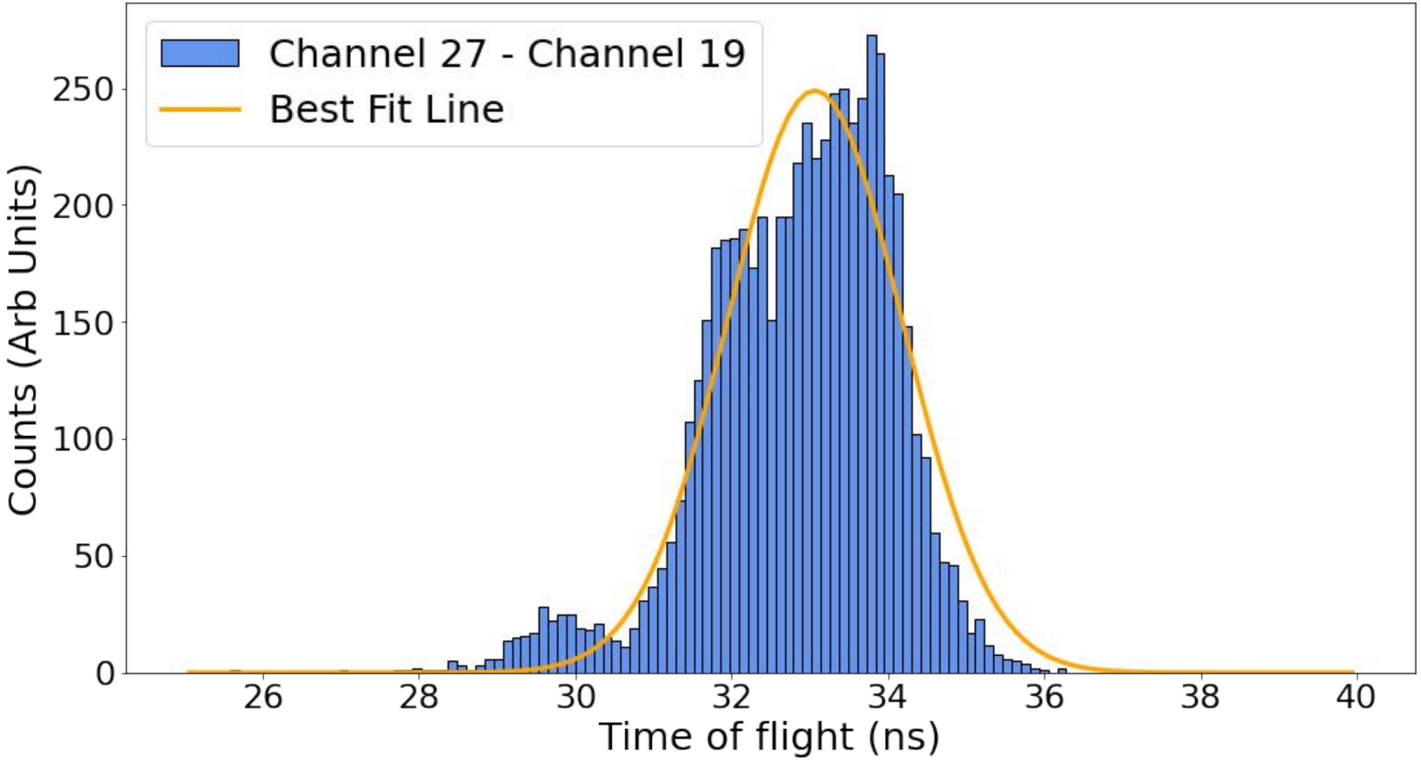
Time of Flight Measurement Results



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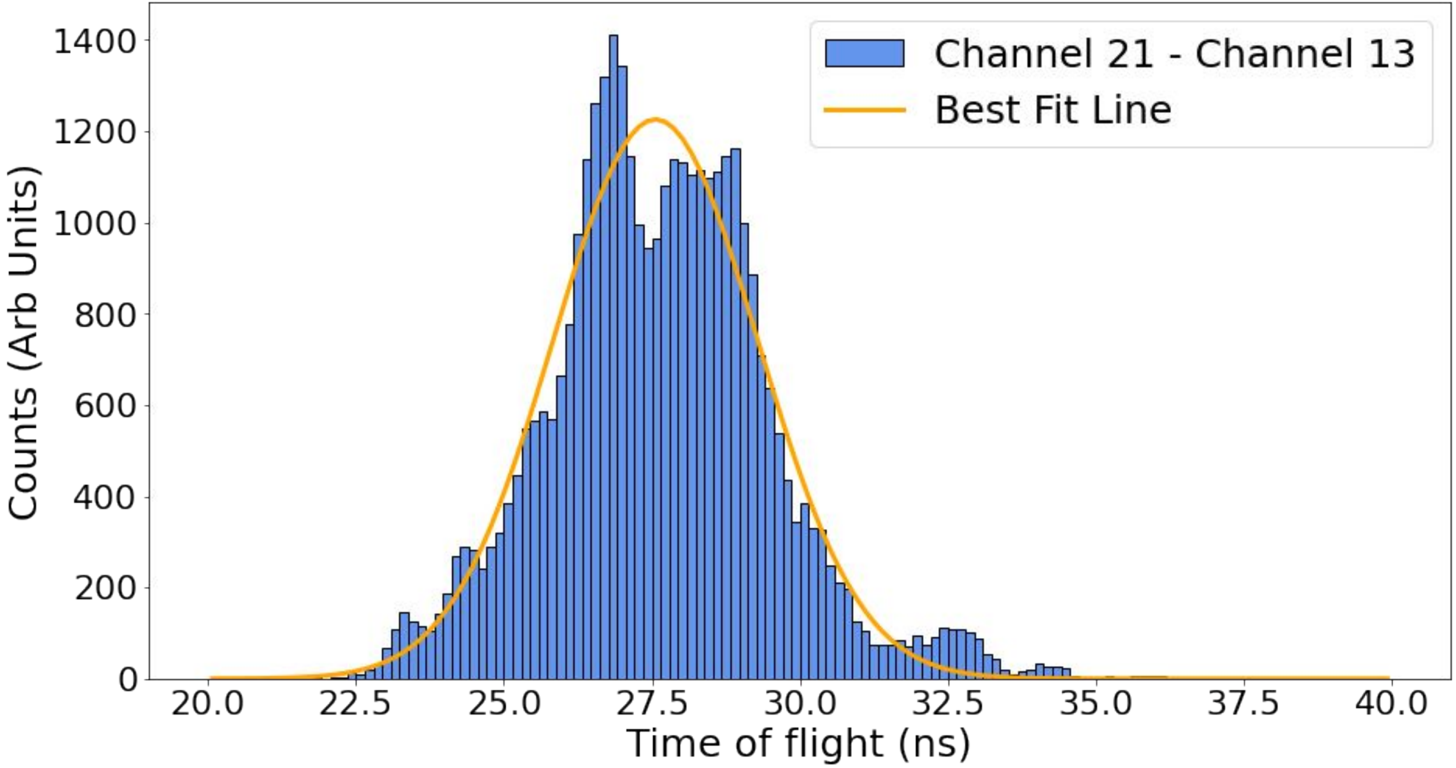
Gaussian fit was performed on the ToF measurement:
ToF = 33.06 ns | σ_{ToF} = 1.12 | Quasi χ^2/dof = 1.584
$\sigma_{\text{Counts in each bin}}$ = 15 counts

Time of Flight Measurement Results Cont.

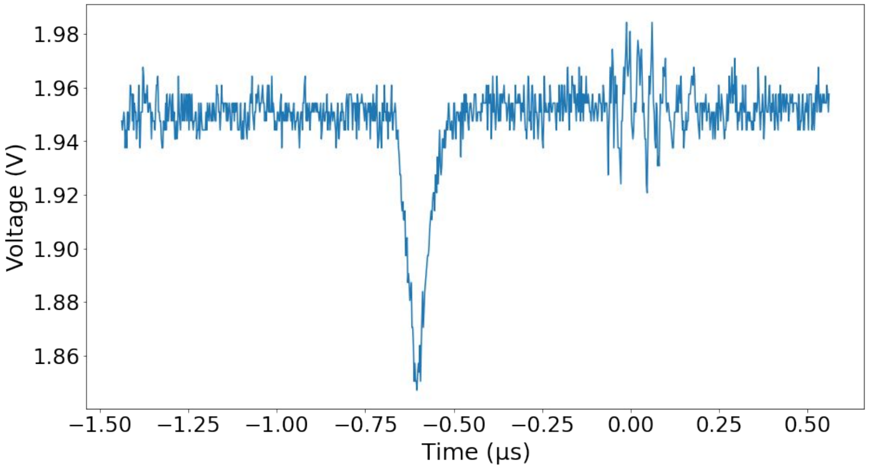


Gaussian fit was performed on the ToF measurement:

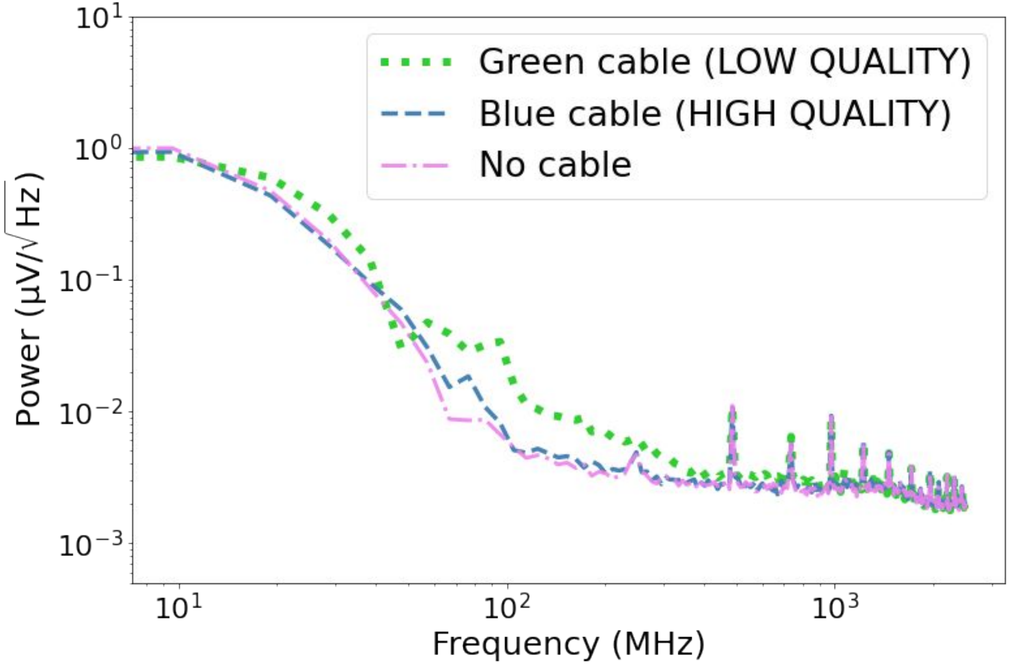
ToF = 27.56 ns | σ_{ToF} = 1.72 | Quasi χ^2/dof = 27.505

$\sigma_{\text{Counts in each bin}}$ = 15 counts

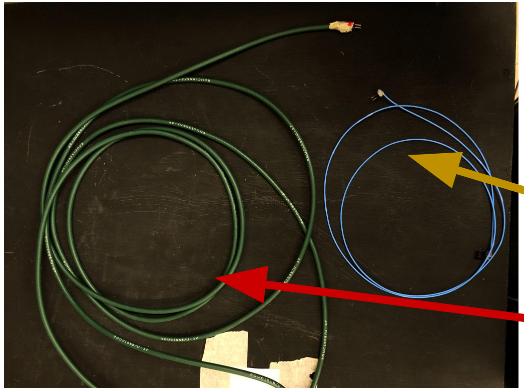
Noise Debugging



Pre-amplifier signal output of the CAEN DAQ



Noise measurements of the pre-amplifier

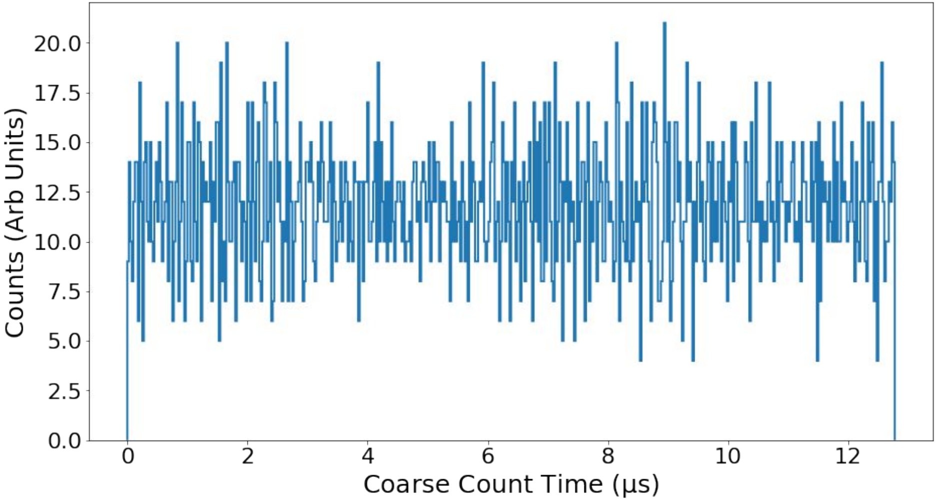


Blue coaxial cable

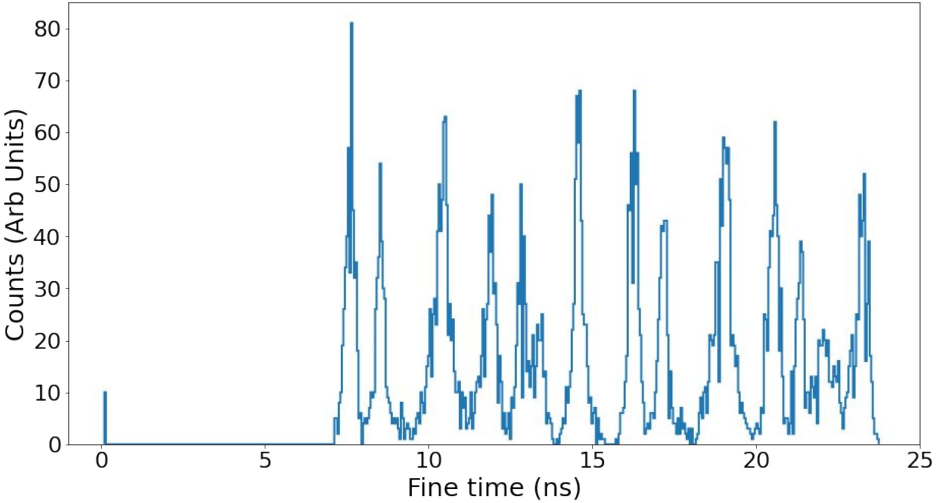
Green coaxial cable

- Very high frequency noise similar
- Low frequency noise higher in green
  - Long wires
  - Self-induction

Coarse Counter and Fine Time Conversion signals



Coarse counter distribution for a select channel during time measurement



Fine time ADC distribution for the same channel as the coarse counter during time measurement

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- Laser not synchronized to DAQ clock
  - Should trigger DAQ at random times
- Both distributions expected to be uniform
  - Fine time shows unexpected peaks

Module Prototype

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Module Design Considerations

1. Similar to MATHUSLA module
2. Easy to level and stable
3. Durable and will not collapse
4. Height adjustability
5. Simple layer exchange
6. Wiring and electronics connections

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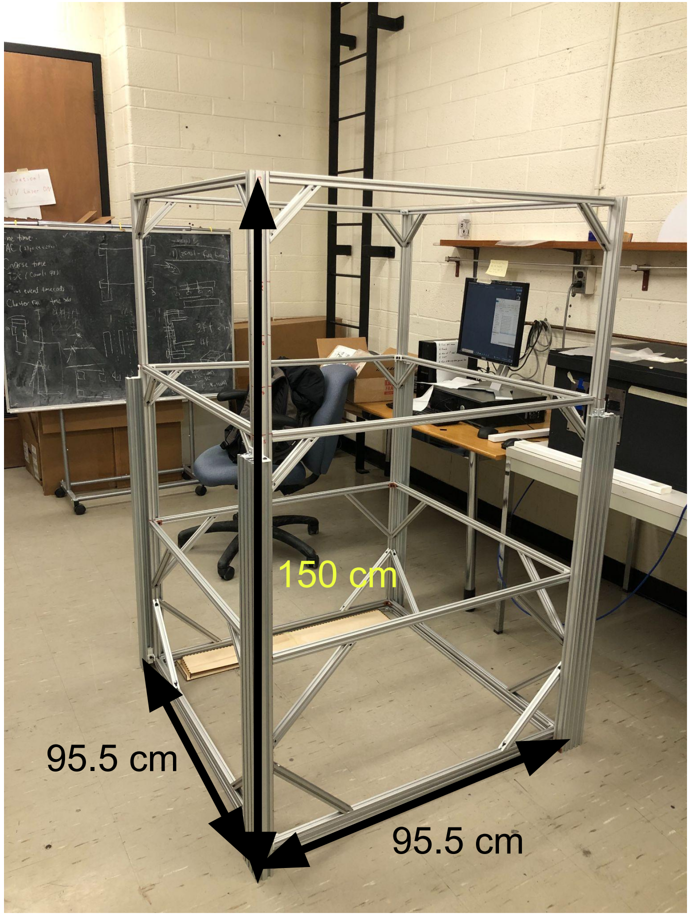
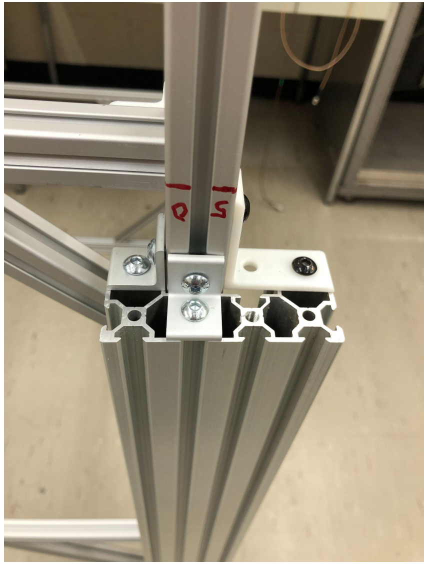
Module Frame

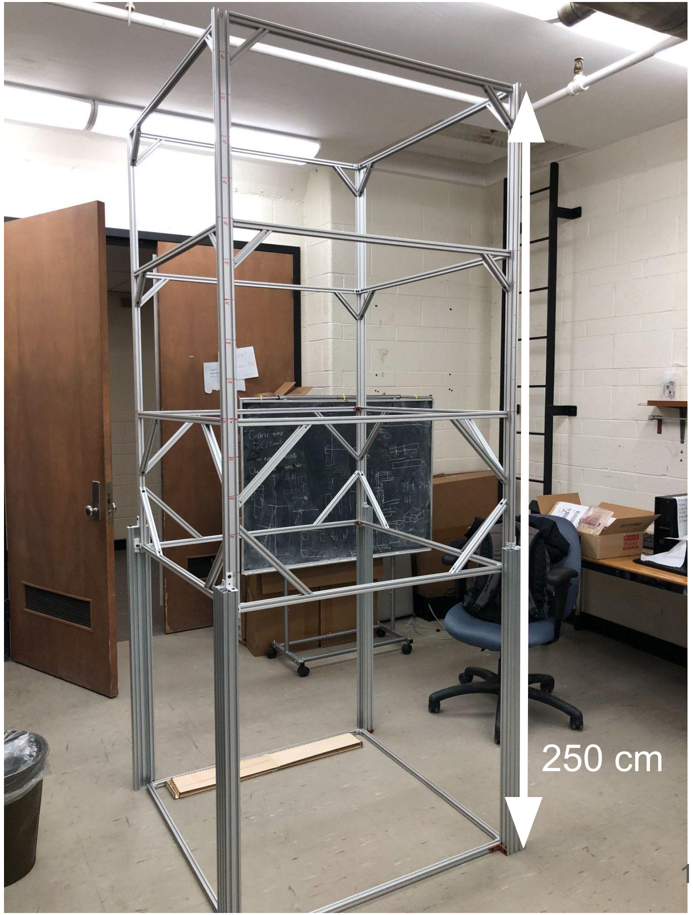


Left: Module frame in its lowest height

Right: Module frame raised to max height

Bottom: “Braking” connectors for sliding mechanism to hold the module height





Layer Connector

Base layer connection to the frame's leg

Scintillation layer connection to module frame

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SiPM Holder Considerations

1. Holds wire flush against SiPM
2. Wire should not move around
3. Easy assembly
4. Light-tight box design
5. Profile of holder should be similar to Scintillator bar
6. Can be easily attached to module frame
7. Electronics readout connections

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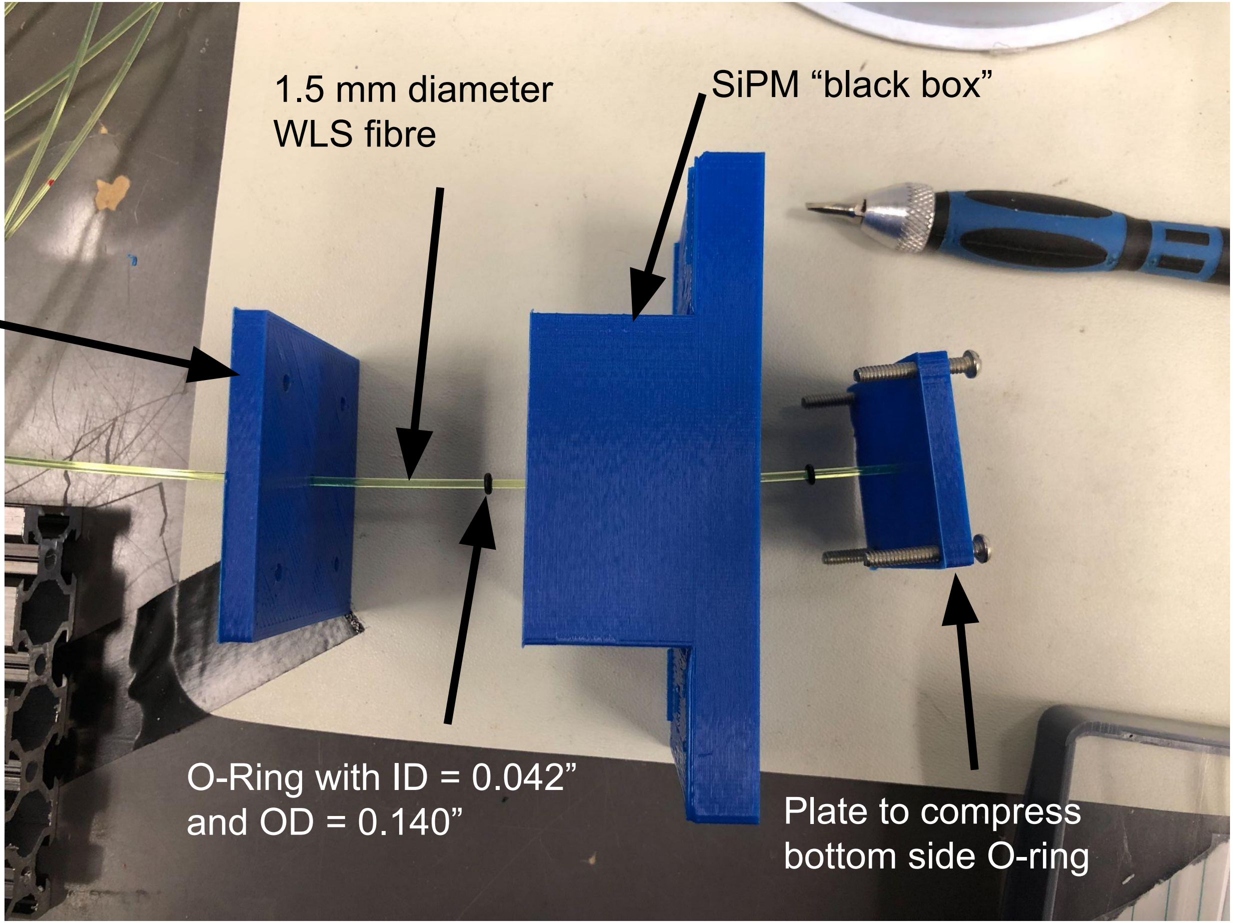
SiPM Connector

Plate to
compress
top-side
O-ring



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Scintillator Layer 2-Bar Connection

Plastic
Scintillator bar

1.5 mm
diameter
WLS fibre

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Future Work

- Test the CAEN DAQ system with a faster SiPM
  - Currently using Broadcom SiPMs and seeing a rising edge duration of > 5 ns. Will a faster SiPM improve the ToF measurements?
- Module and Holder wiring
  - PCB design for SiPM readout
  - Wire connections from SiPM PCB to DAQ
- Module Stability issues
  - Wobbly when extended to max height, need some version of bracing at the bottom of the sliding rail to lessen the weight carried by the “brakes” and improve stability
- Module detector layer connectors
  - Better adapter piece for building the layers — should be easy to remove a id or the layer to replace scintillator bars in layer (must be modular)
- Light-tight box design
  - Light proofing SiPM holder, layer connector and entire frame

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Thank you! Questions?

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References

[1] E. Le Boulicaut, “The Standard Model.” [Online]. Available: https://cds.cern.ch/record/2759492/files/Standard%20Model%20-%20ATLAS%20Physics%20Cheat%20Sheet.pdf

[2] A. H. G. Peter, “Dark Matter: A Brief Review,” arXiv e-prints, p. arXiv:1201.3942, Jan. 2012.

[3] J. L. Feng, “Naturalness and the status of supersymmetry,” *Annual Review of Nuclear and Particle Science*, vol. 63, no. 1, pp. 351–382, 2013. [Online]. Available: https://doi.org/10.1146/annurev-nucl-102010-130447

[4] The Large Hadron Collider.” [Online]. Available: https://www.home.cern/science/accelerators/large-hadron-collider

[5] J. Pequenao and P. Schaffner, “How ATLAS detects particles: diagram of particle paths in the detector,” 2013. [Online]. Available: https://cds.cern.ch/record/1505342

[6] The MATHUSLA experiment.” [Online]. Available: https://mathusla-experiment.web.cern.ch/

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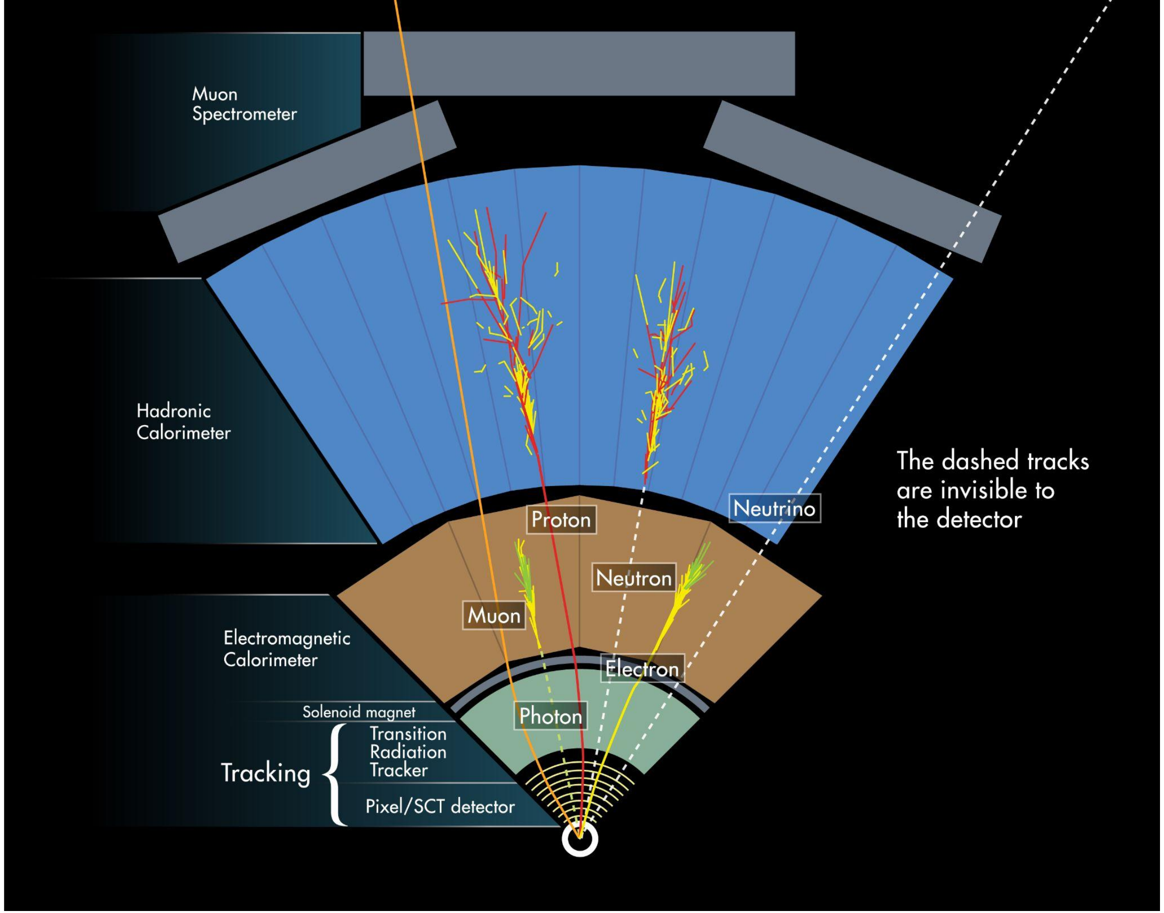

Figure 2: Cross-section of a sector of the ATLAS detector with select particle signatures [5]

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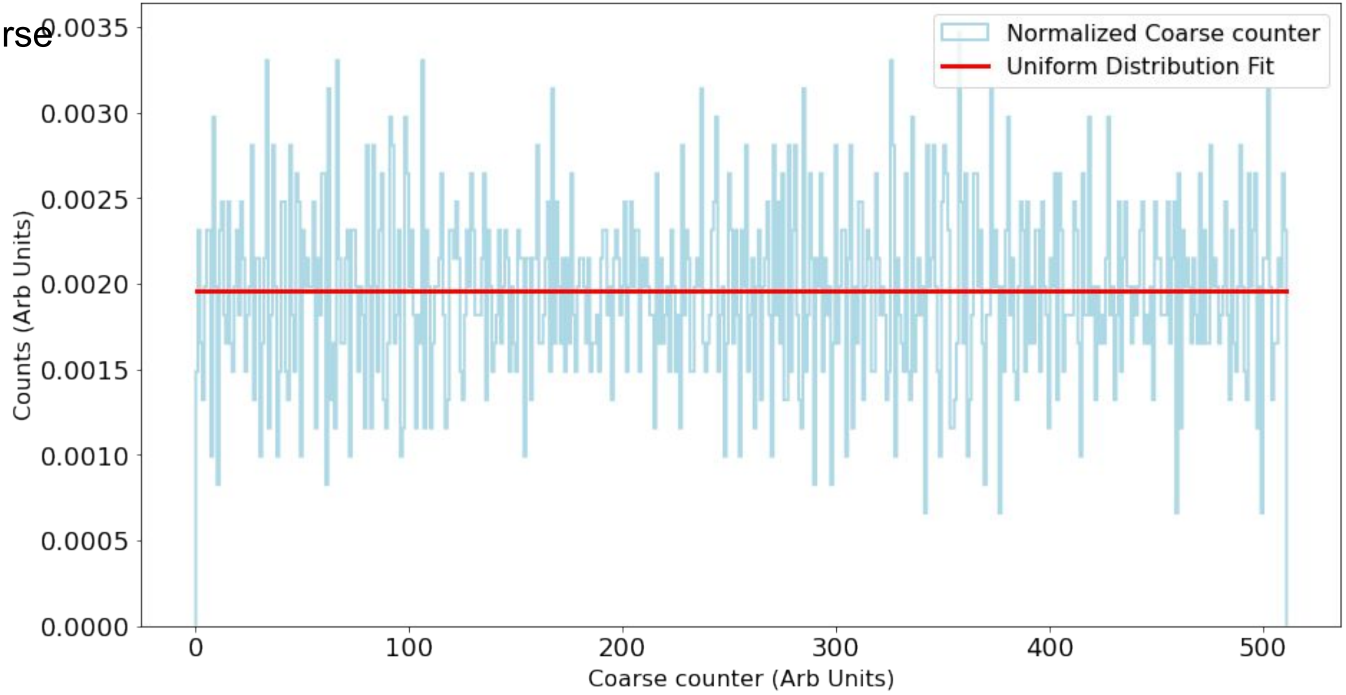
Coarse Counter Fitted Signal

Area under normalized coarse counter histogram:
A = 0.9982

Fitted uniform PDF:
p(x) = 0.0019589

Expected:
p(x) = 0.00195313



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Fine Time Conversion Formula and ToF calculation

$$ToF = ((coarse_1 + 1) \times 25 \text{ ns} - fine_1) - ((coarse_2 + 1) \times 25 \text{ ns} - fine_2)$$

$$fine_{ns} = (fine - fine_{min}) \times \alpha$$

$$\alpha = \frac{25 \text{ ns}}{fine_{max} - fine_{min}}$$

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